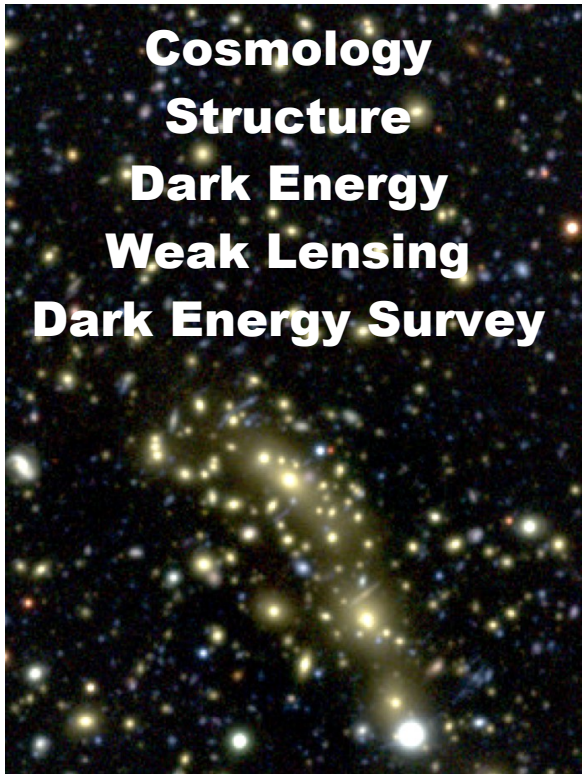
Unveiling dark energy and dark matter with weak gravitational lensing

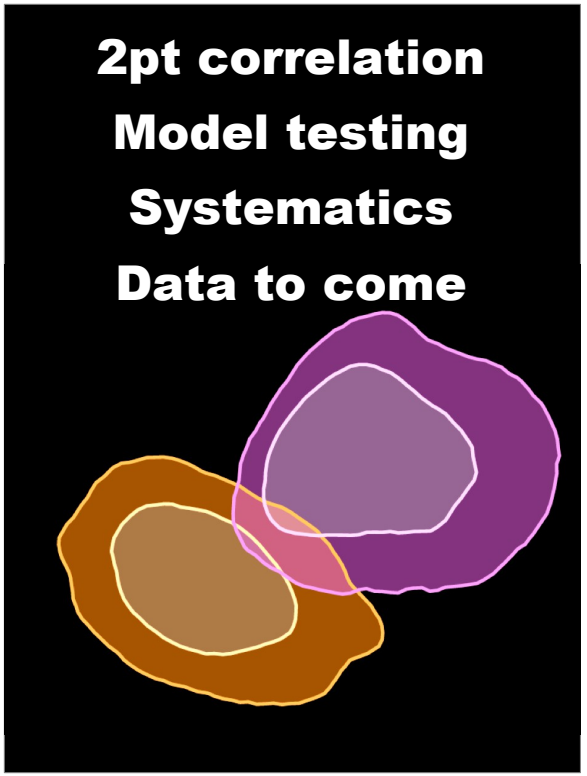
Daniel Gruen, Stanford

SLAC, 2019-02-07

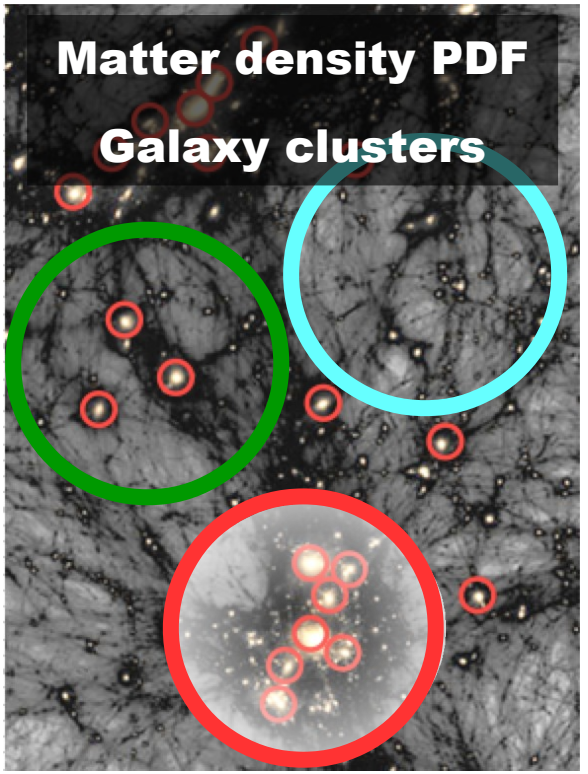
Introduction



Cosmology from Lensing



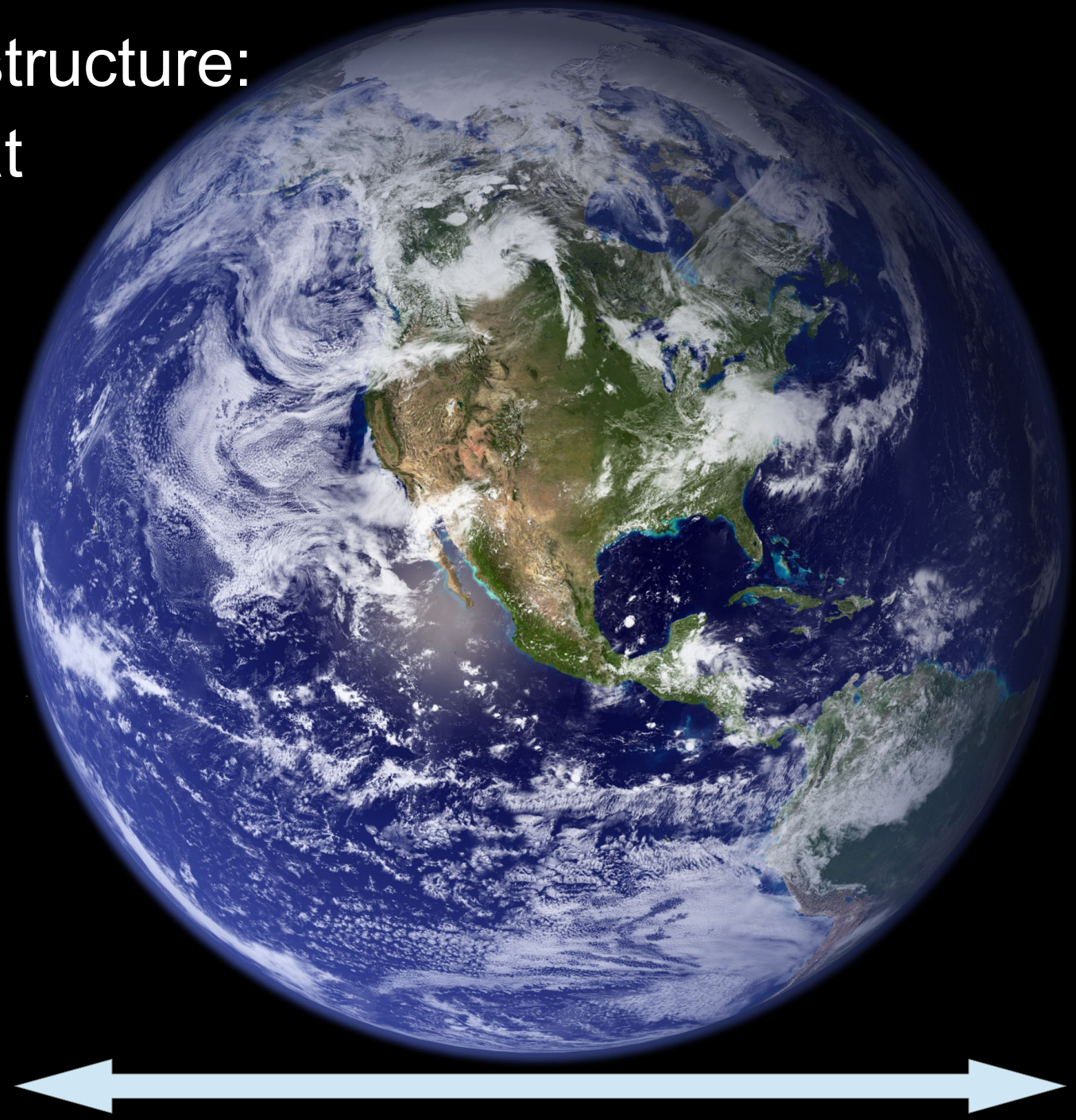
Beyond the power spectrum



LSST
Large Synoptic Survey Telescope

Questions welcome!

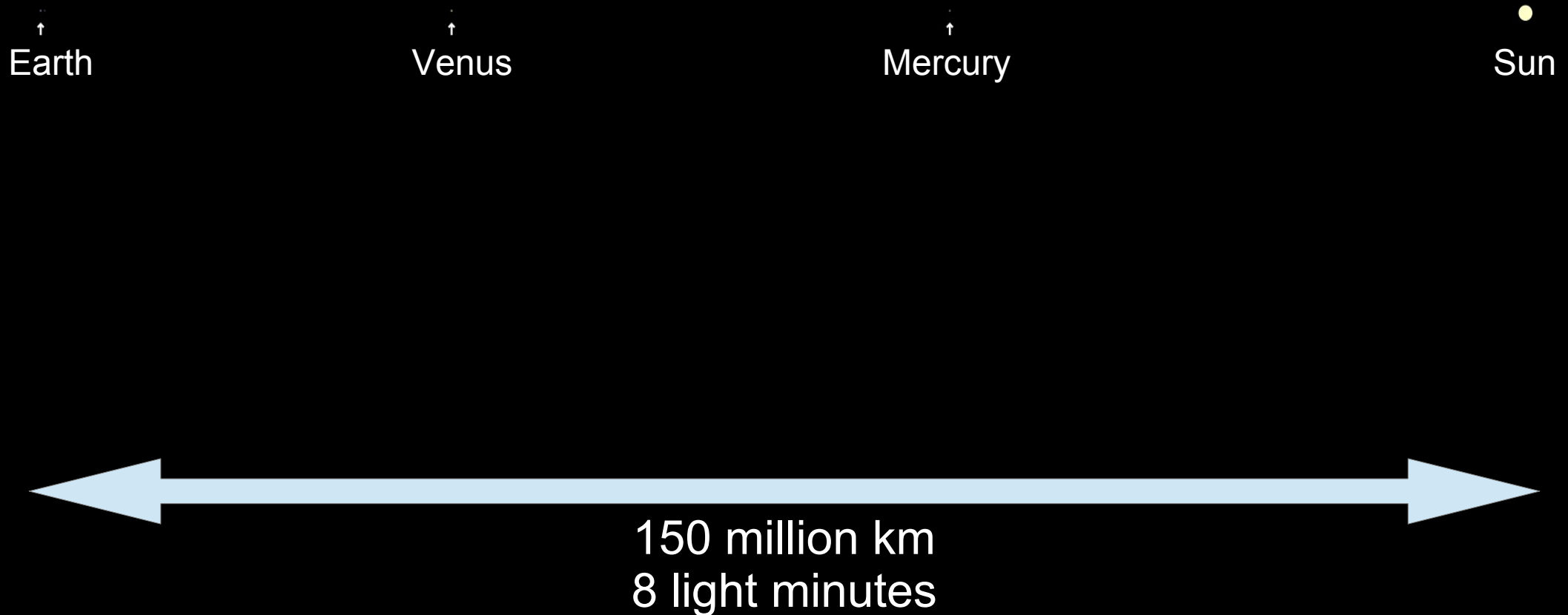
Cosmic structure: starting at the Earth

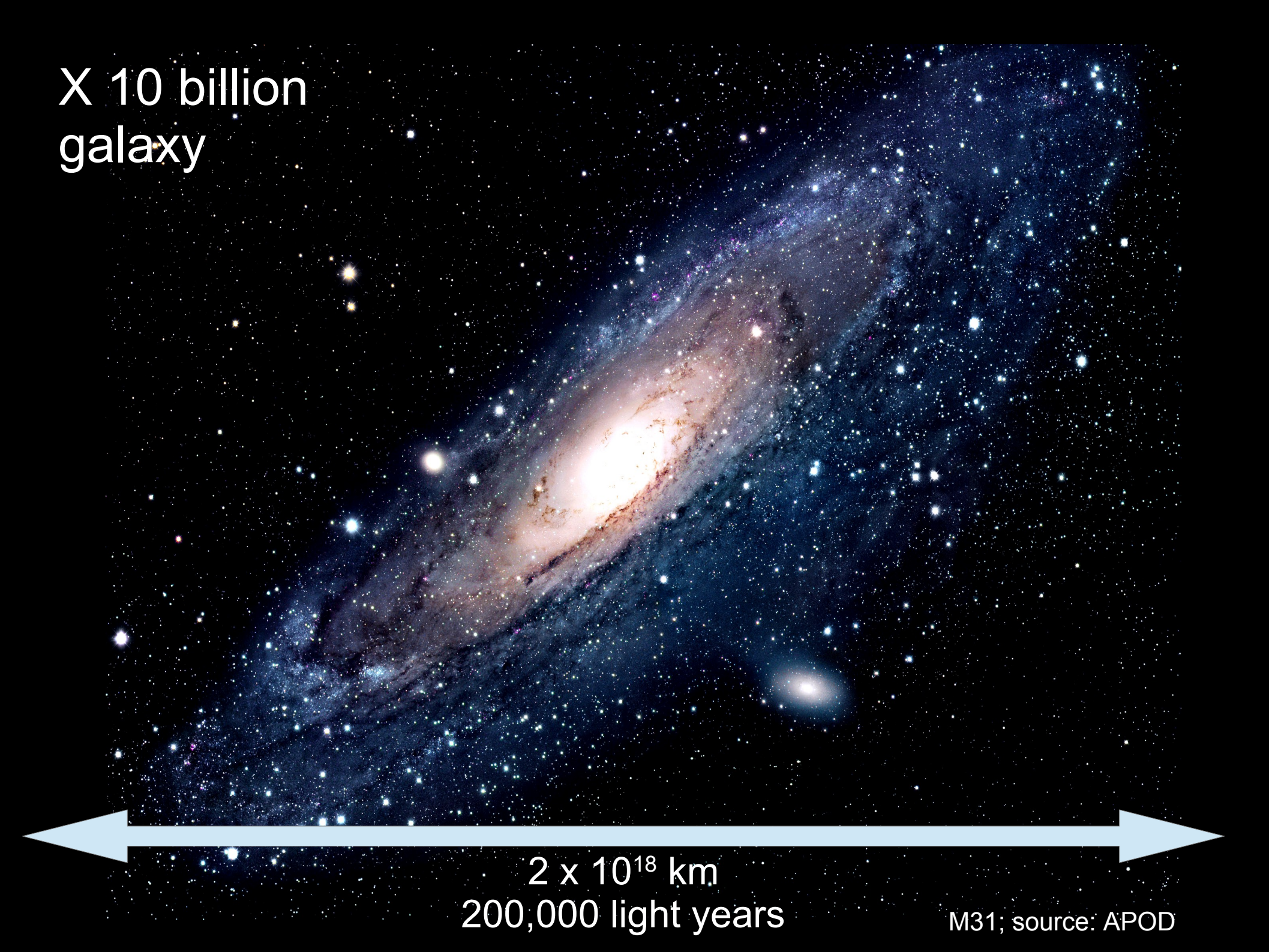


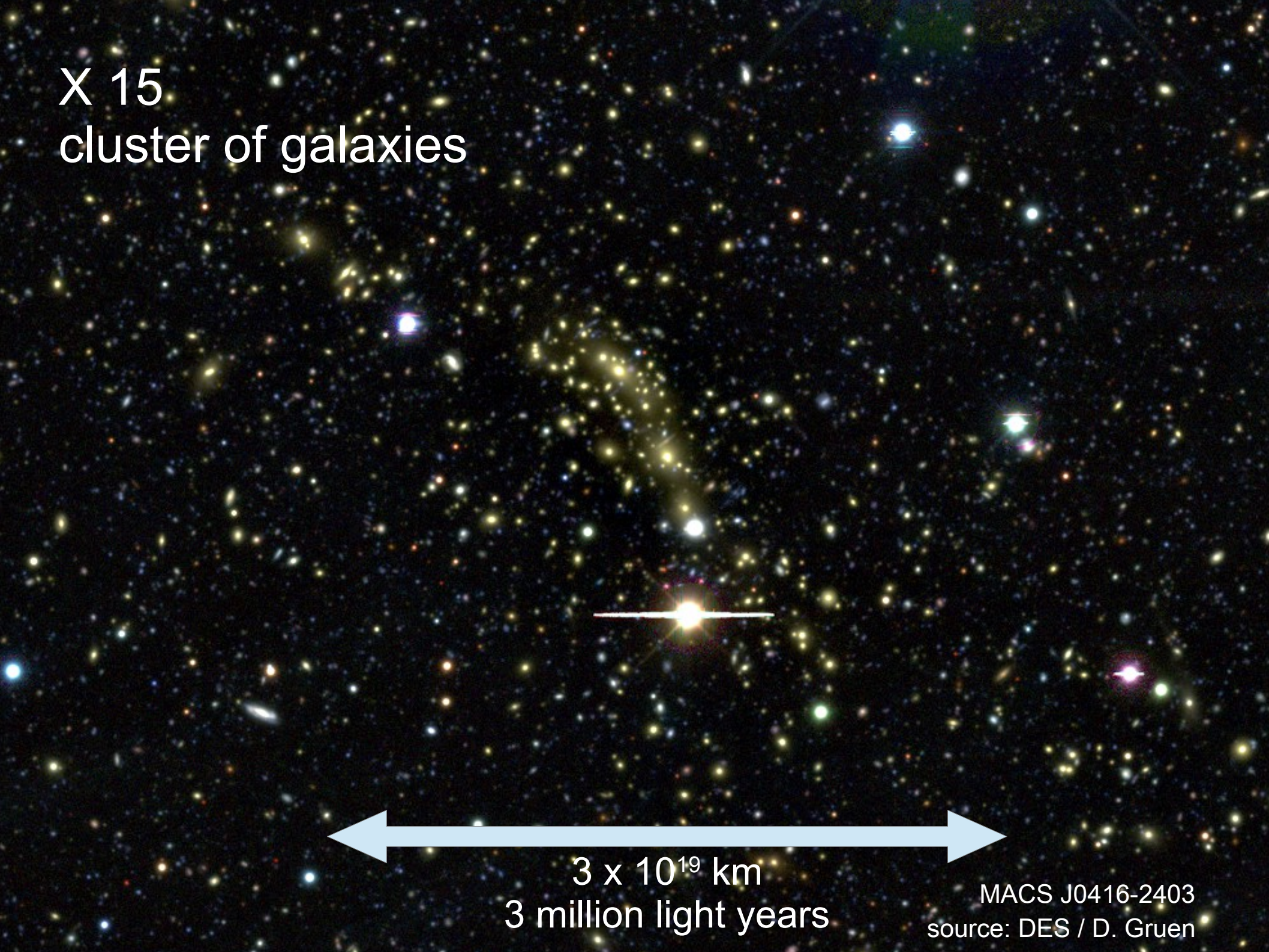
13,000 km
0.04 light seconds

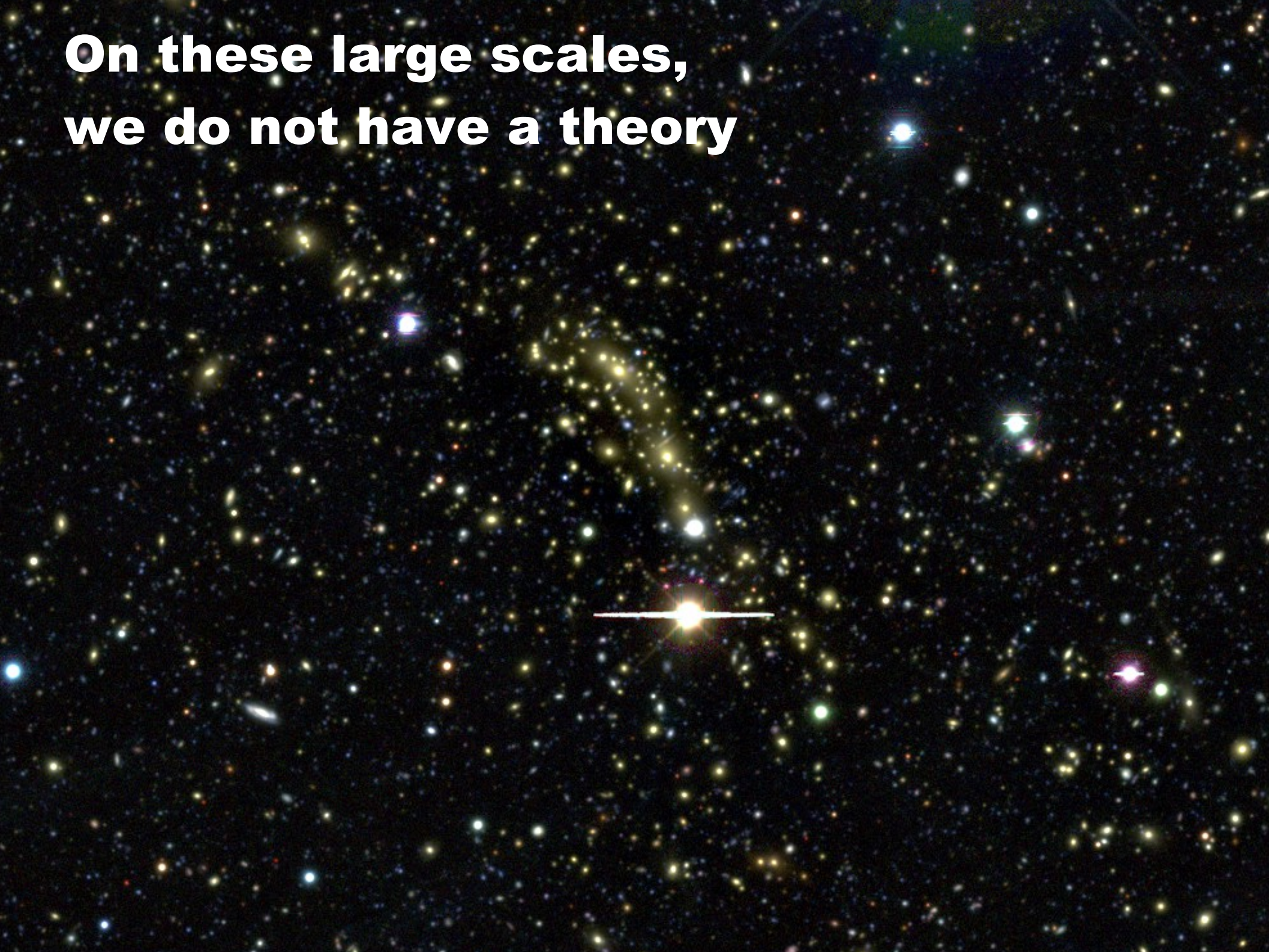
source: NASA/MODIS

X 10,000
inner solar system




X 10 billion
galaxy
2 x 10^18 km
200,000 light years
M31; source: APOD


X 15
cluster of galaxies
3 x 10^19 km
3 million light years
MACS J0416-2403
source: DES / D. Gruen


On these large scales,
we do not have a theory

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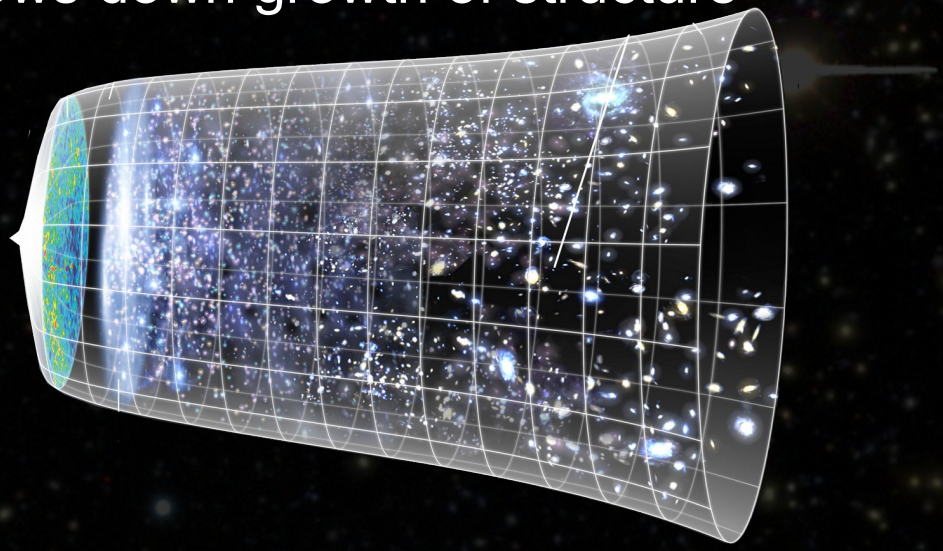
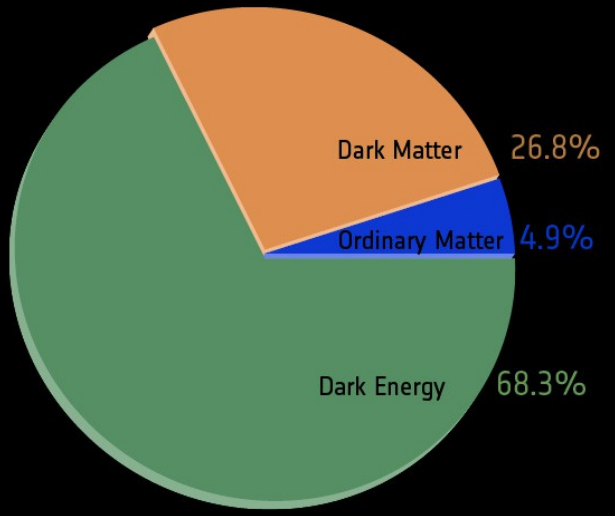
Cosmic Frontier

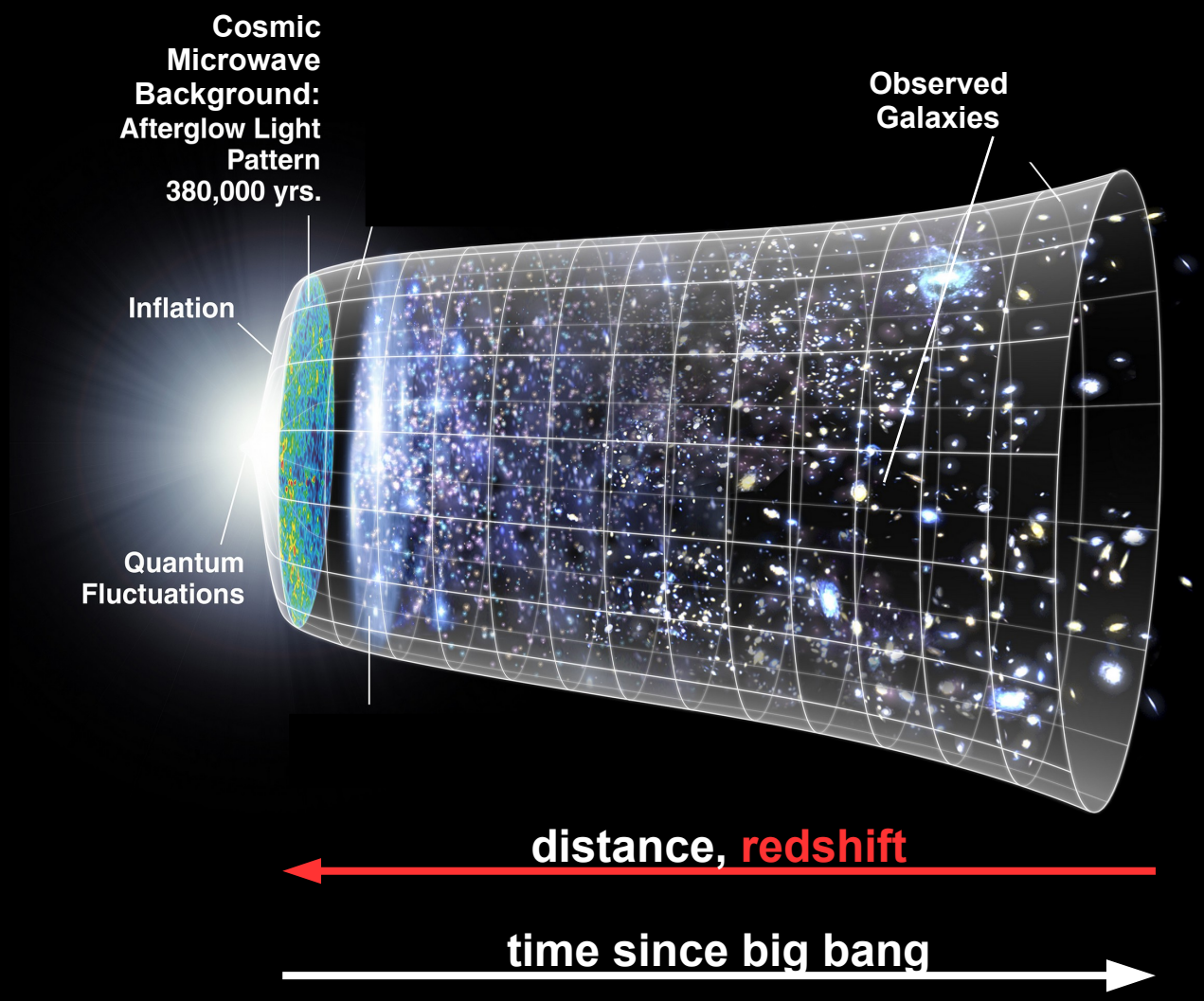
ΛCDM model:

- 80% of matter is a non-standard-model substance
  - "Dark Matter", only interacts via gravity
- 70% of energy is an unknown substance, consistent with cosmological constant / vacuum energy, $10^{<-50}$ x QFT value
  - "Dark Energy", accelerates cosmic expansion, slows down growth of structure





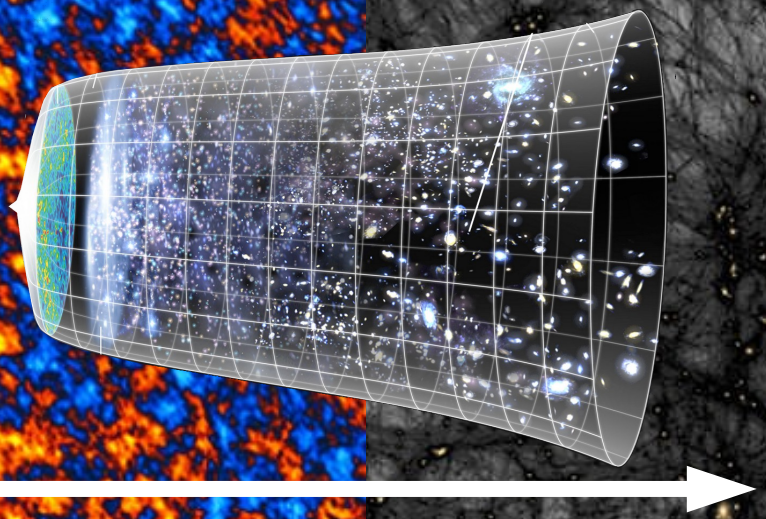
Observing our strange Universe



Credit: WMAP/DES/LSST

Structure in the Universe: then and now

CMB temperature,
Planck satellite



Simulated structure today

Credit: Ralf Kaehler, Carter Emmart, Tom Abel, Oliver Hahn / SLAC

10^{10} years later

10^{9} more volume

10^{-5} vs. $10^{>3}$ density contrast

Do Dark Matter and a cosmological constant correctly extrapolate this?

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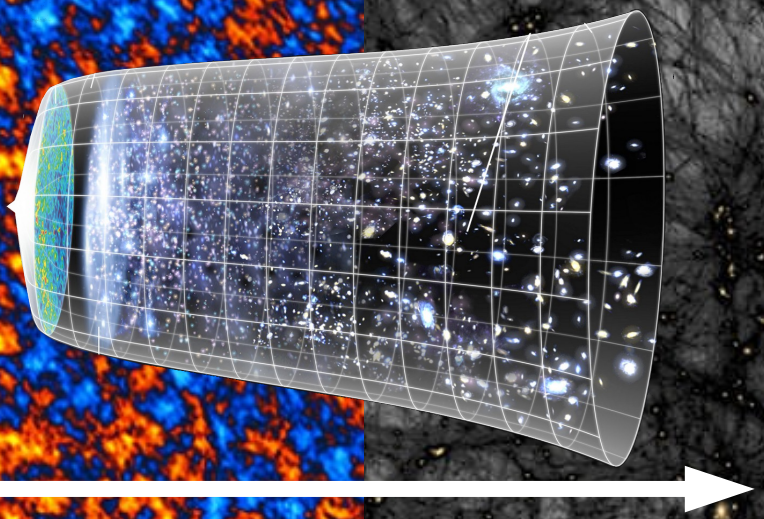

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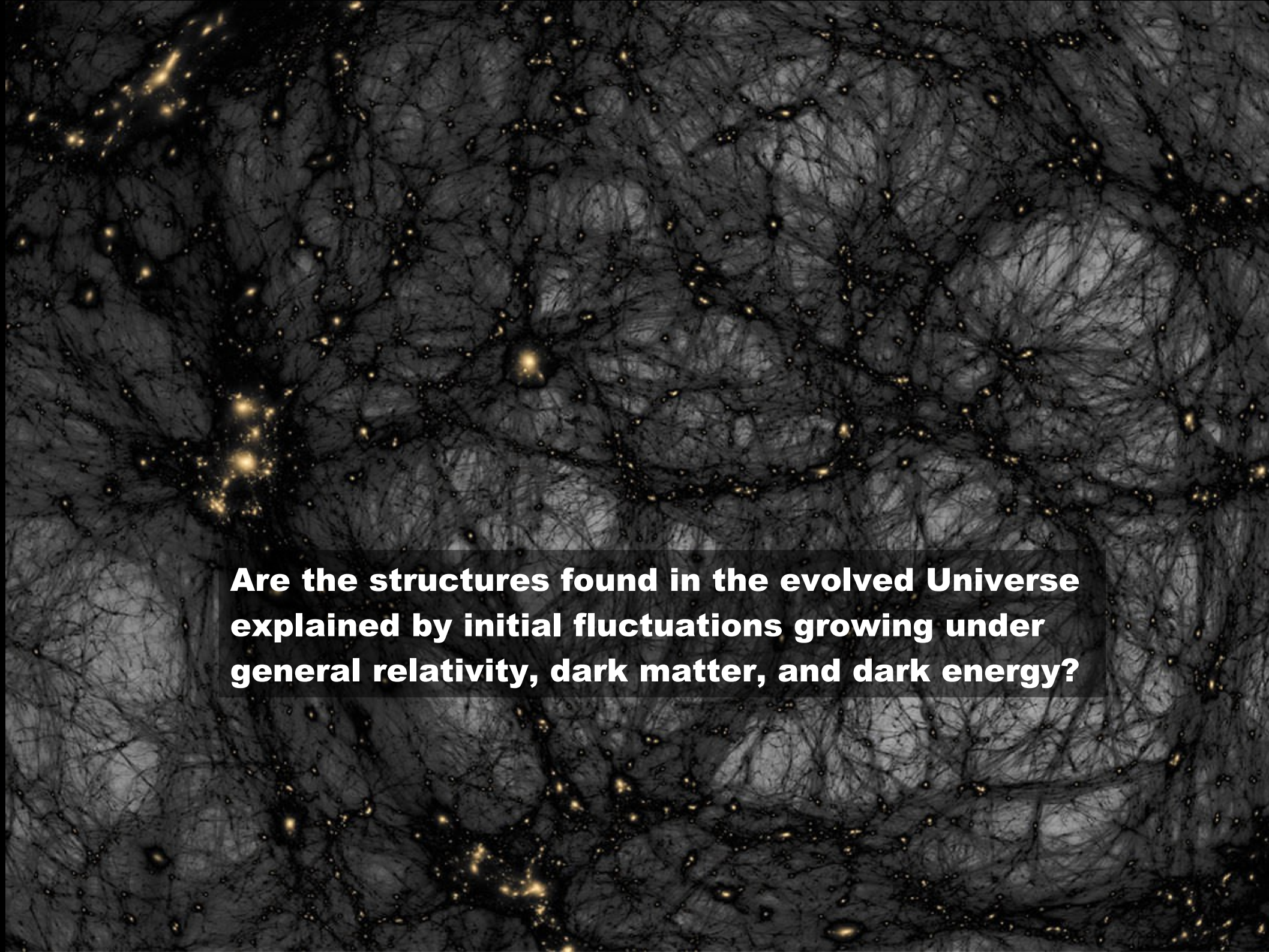
Do Dark Matter and a cosmological constant correctly extrapolate this?

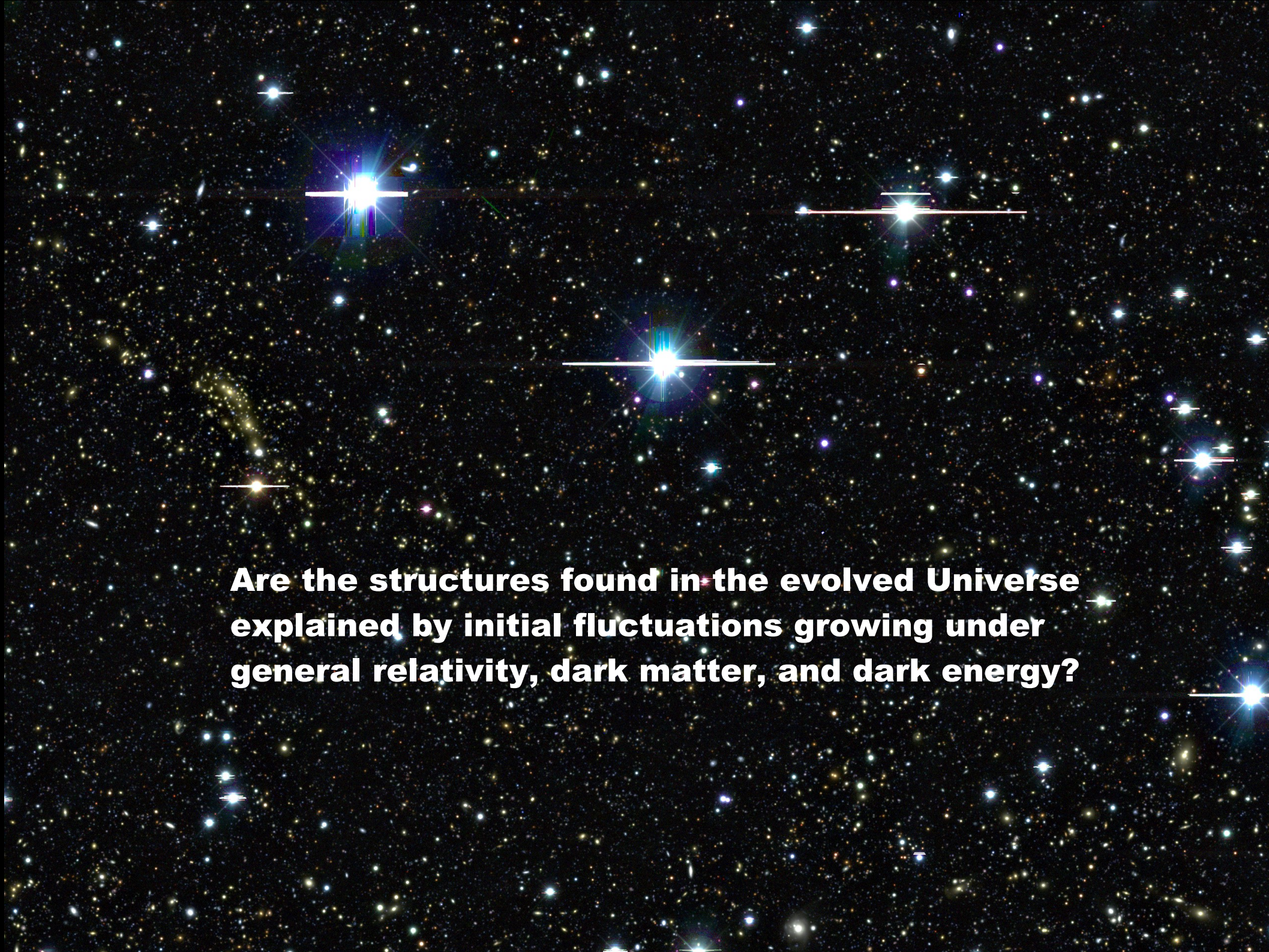
Are data from **early Universe** and **late Universe** fit by the same parameters?

Do **cosmic expansion** and growth of **structure** agree?

Does the dark energy density change as space expands?

"Equation of state" parameter **w=pressure/density**


Are the structures found in the evolved Universe
explained by initial fluctuations growing under
general relativity, dark matter, and dark energy?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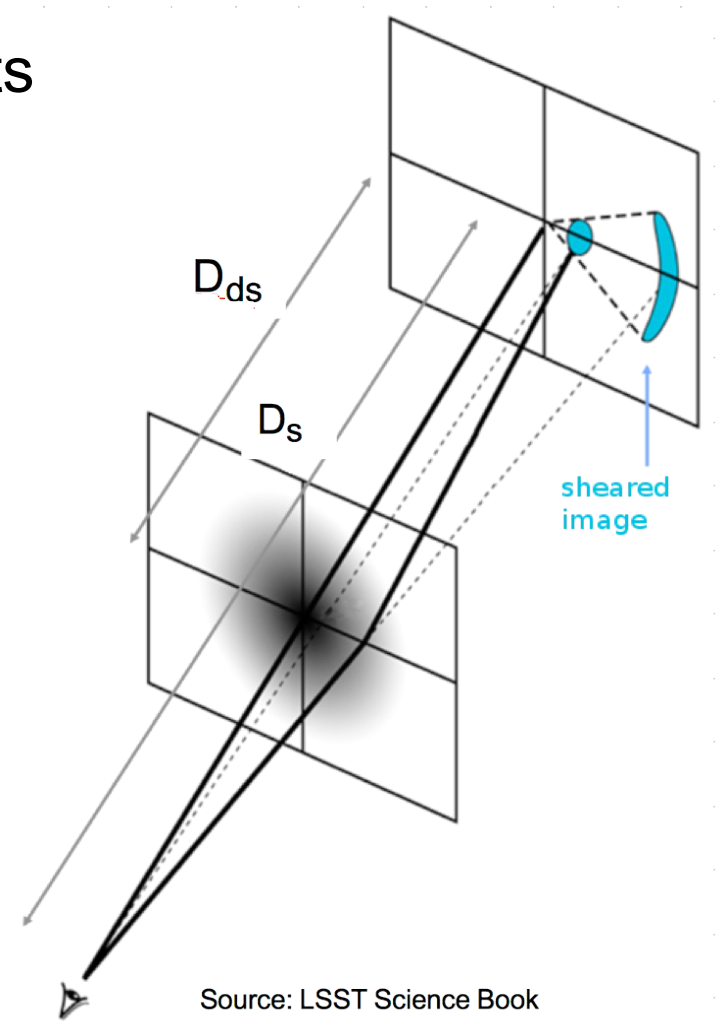
Gravitational lensing

- When light passes massive structures, it feels gravity and its path gets bent
- This causes shifting, and magnification, and shearing of the galaxy image

$$\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$$

$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} \right]$$



Source: LSST Science Book

Enables study of structure by connecting observed images to matter density of lens!

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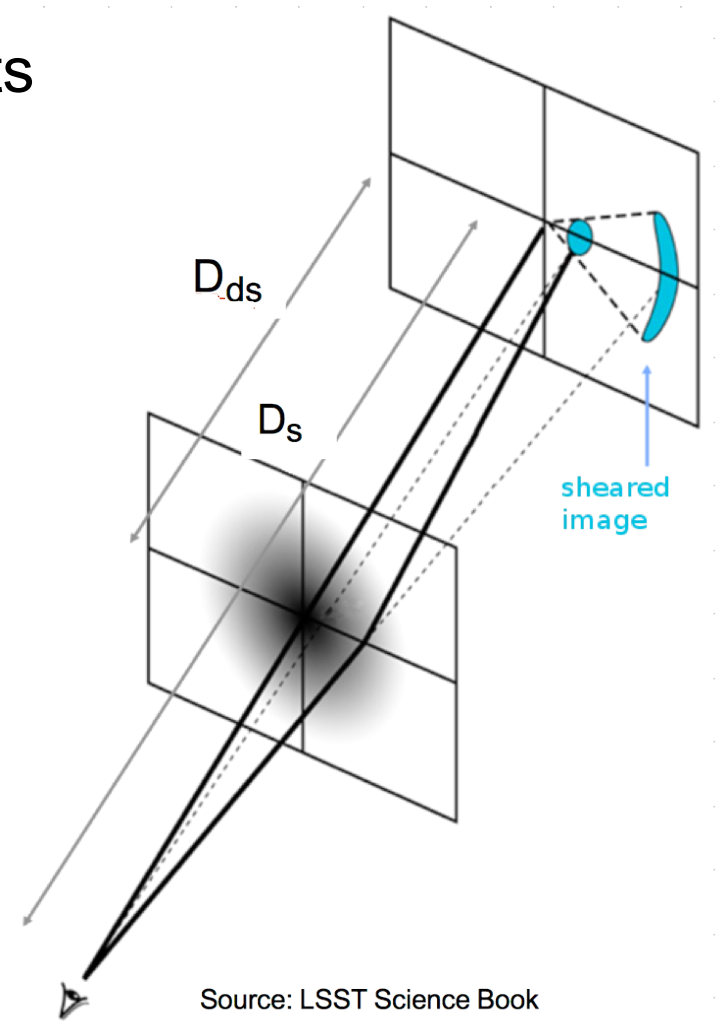

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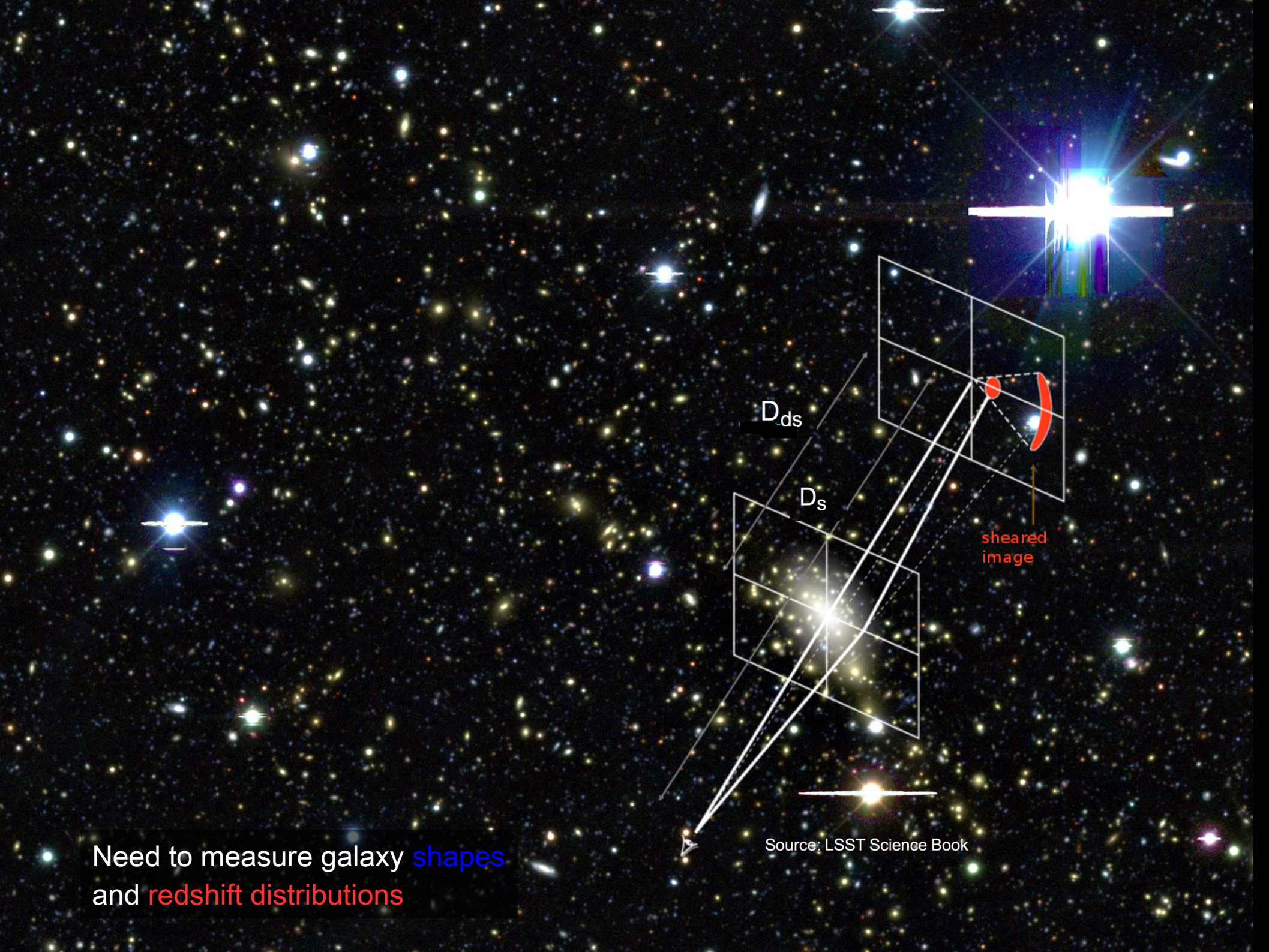
Need to measure galaxy shapes and redshift distributions



Need to measure galaxy shapes and redshift distributions

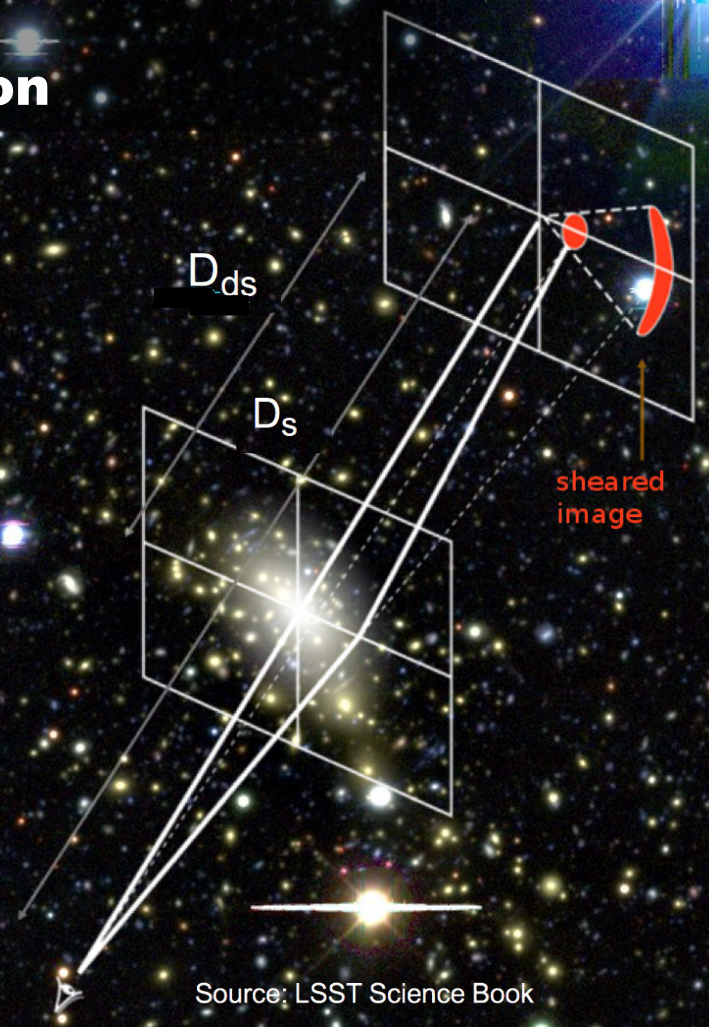
My expertise: **From Pixels to Cosmology**

analyze imaging surveys with **gravitational lensing**,

from accurate **measurements**

to **new statistics of structure**

to **organizing survey collaboration**



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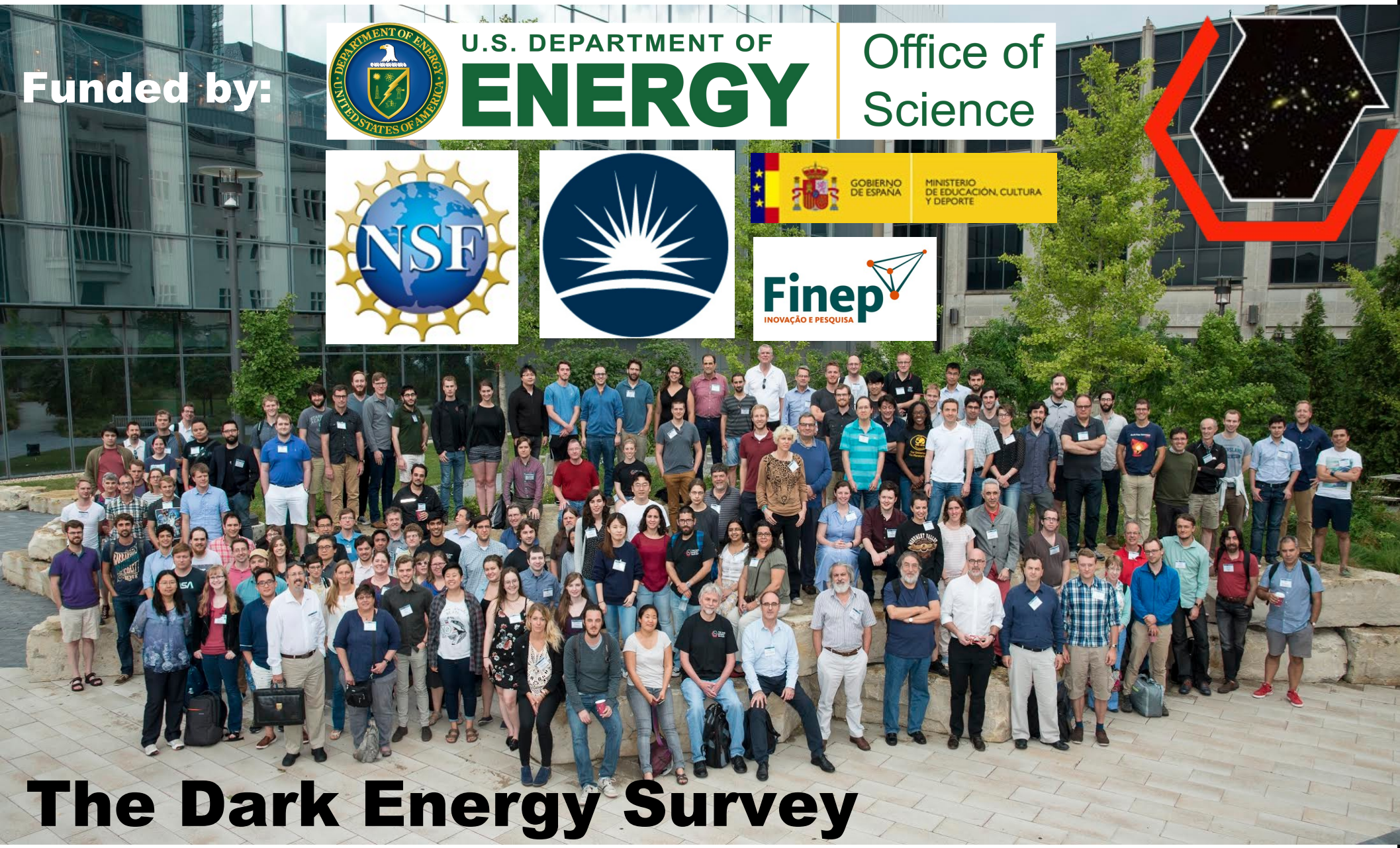
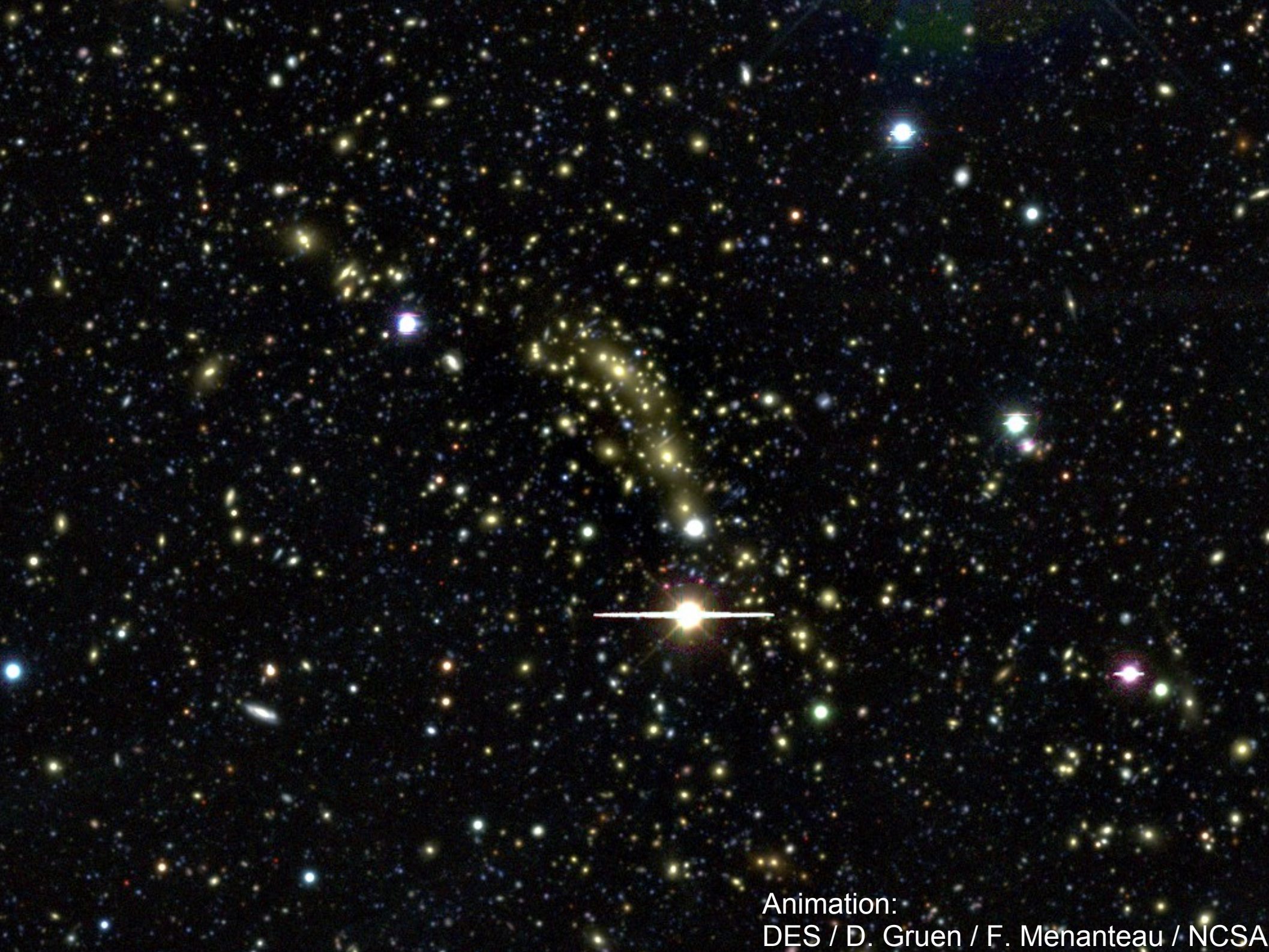


Collaborating institutions:

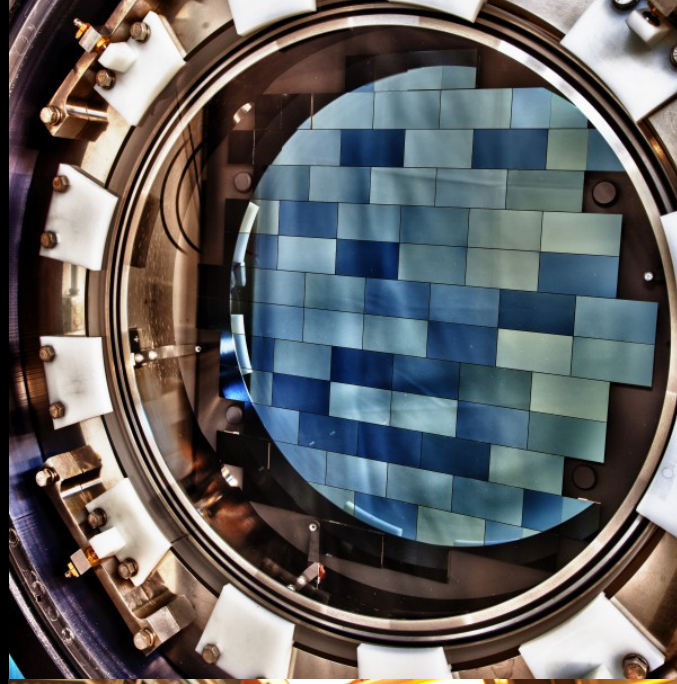

Animation:
DES / D. Gruen / F. Menanteau / NCSA

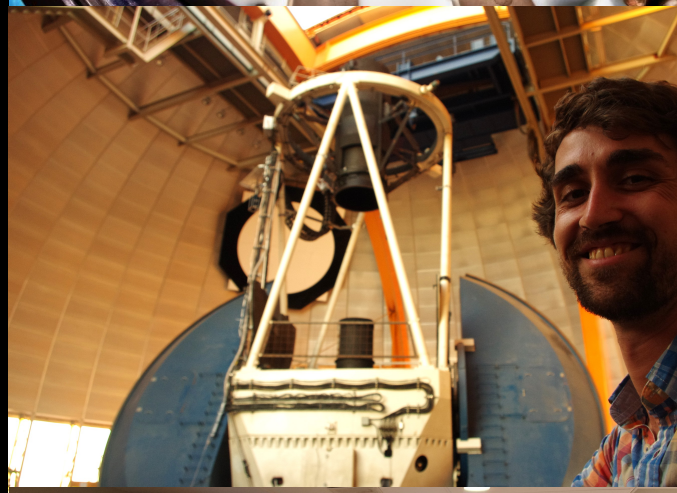
The Dark Energy Survey

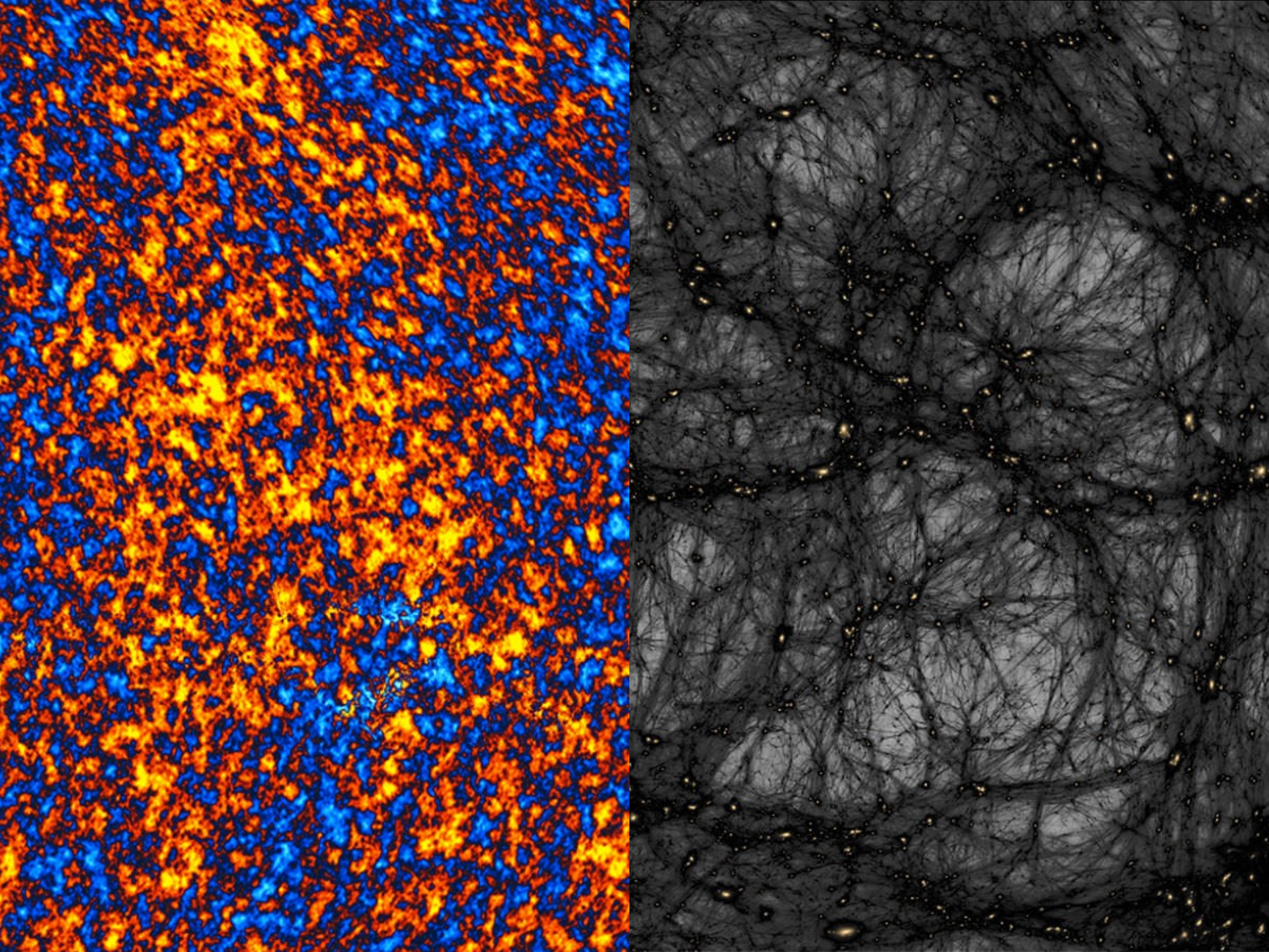
- 5000 sq. deg. in 5 bands from Blanco/CTIO, 10 exposures, 5.5 years, >400 scientists
- Primary goal: dark energy equation of state
- Status:
  - Y1 (1300 sq. deg, 40% depth): key results published / in review
  - Y3 (4000 sq. deg, 50% depth): data processed, vetting catalogs
  - We finished survey as planned on Jan 10

Basic Y3 data and full Y1 value added data public

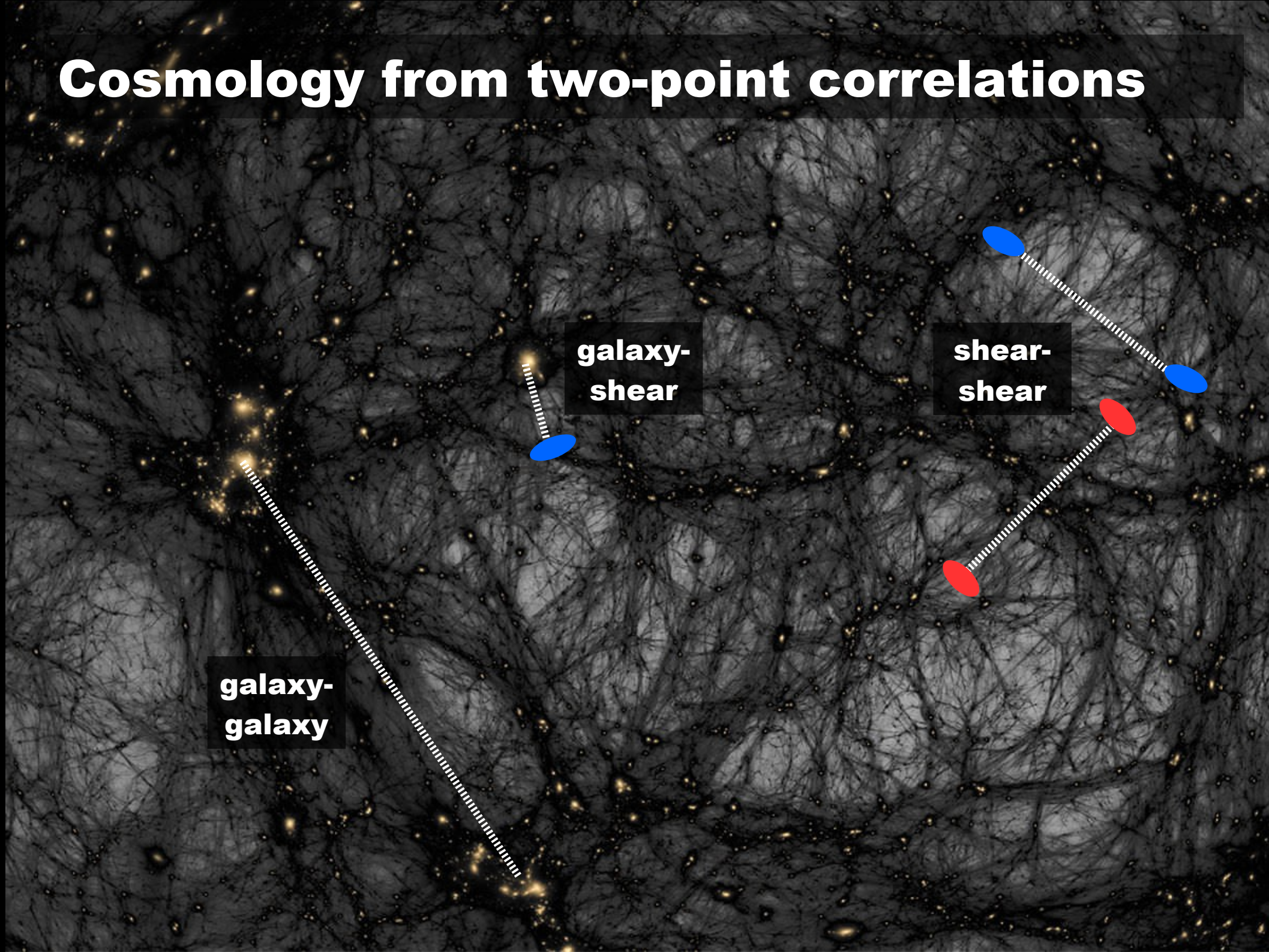
www.darkenergysurvey.org

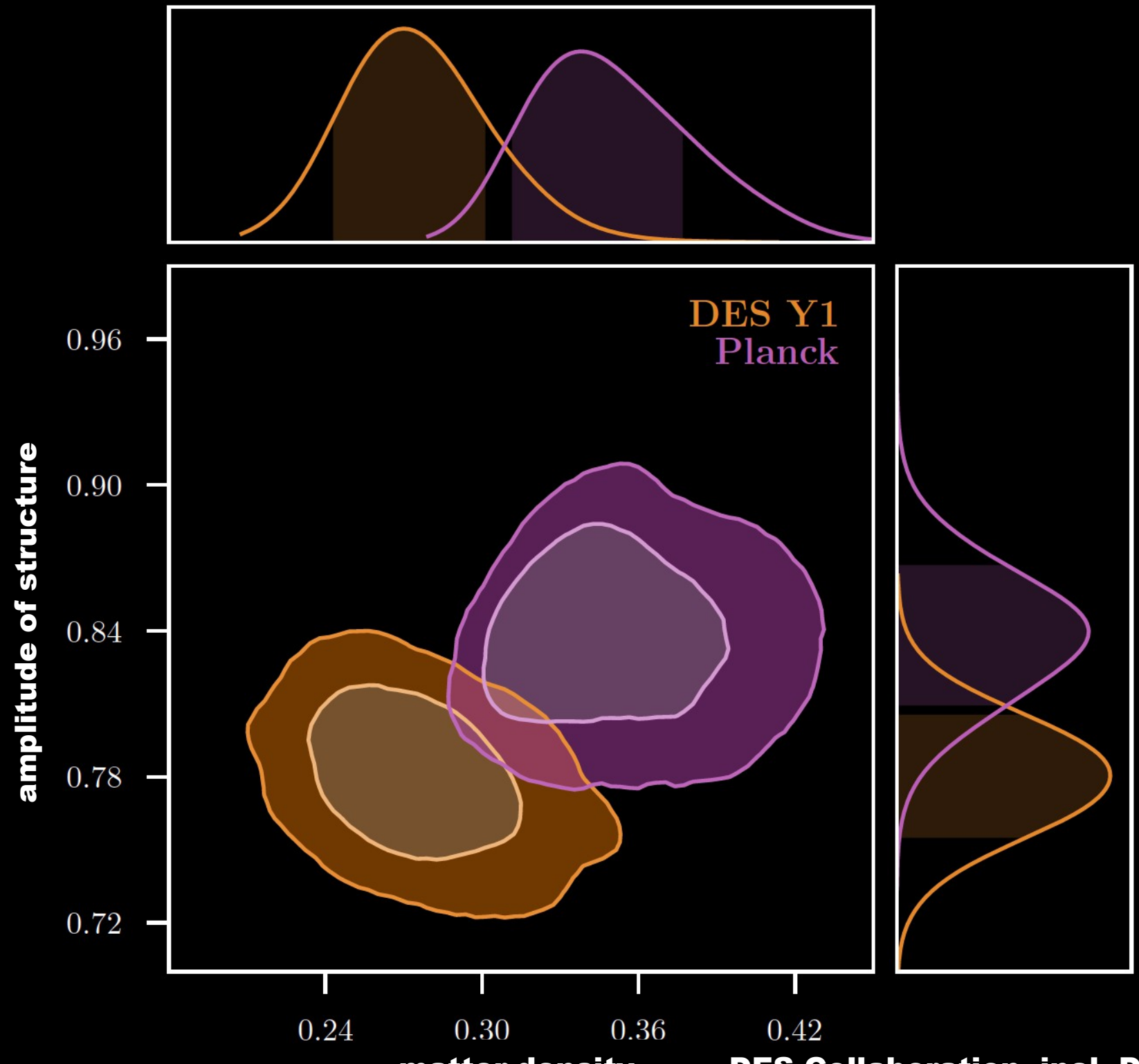






Cosmology from two-point correlations

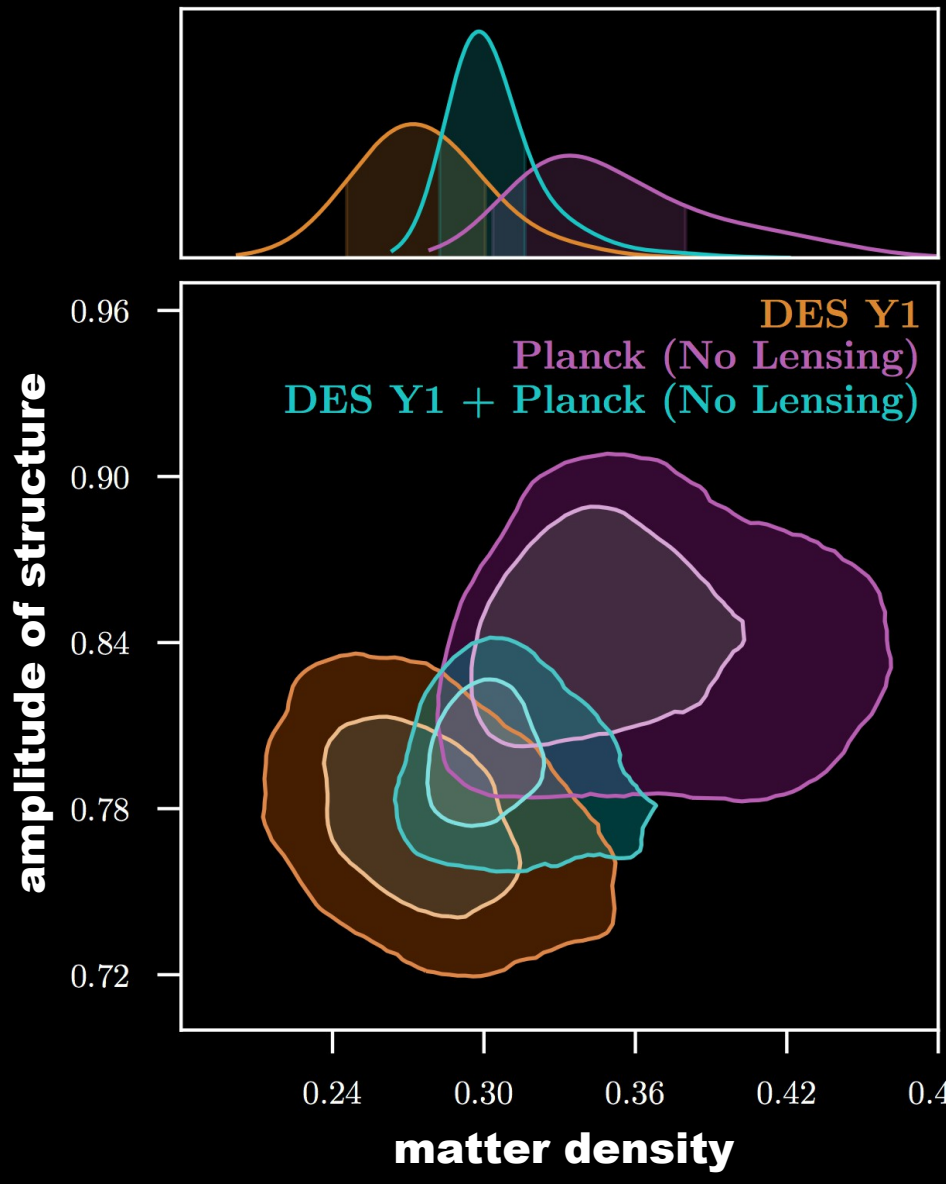




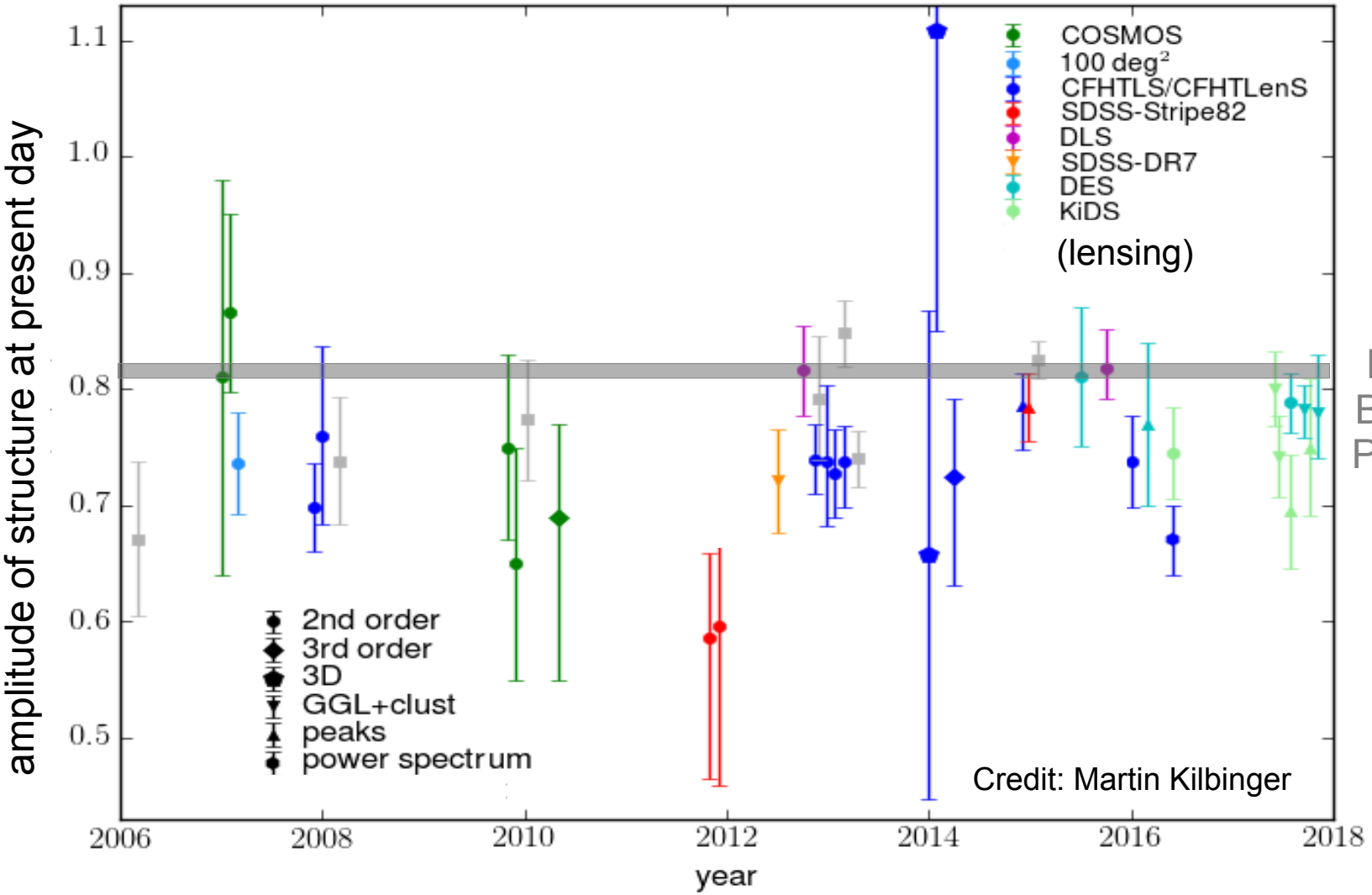
DES Collaboration, incl. DG+ 2018

Consistency of evolved structure with CMB

- DES and CMB constrain matter density and S_8 with equal strength
- Bayes Factor good –
  no evidence for inconsistency
- Difference in central values 1-2σ,
  same direction as earlier results



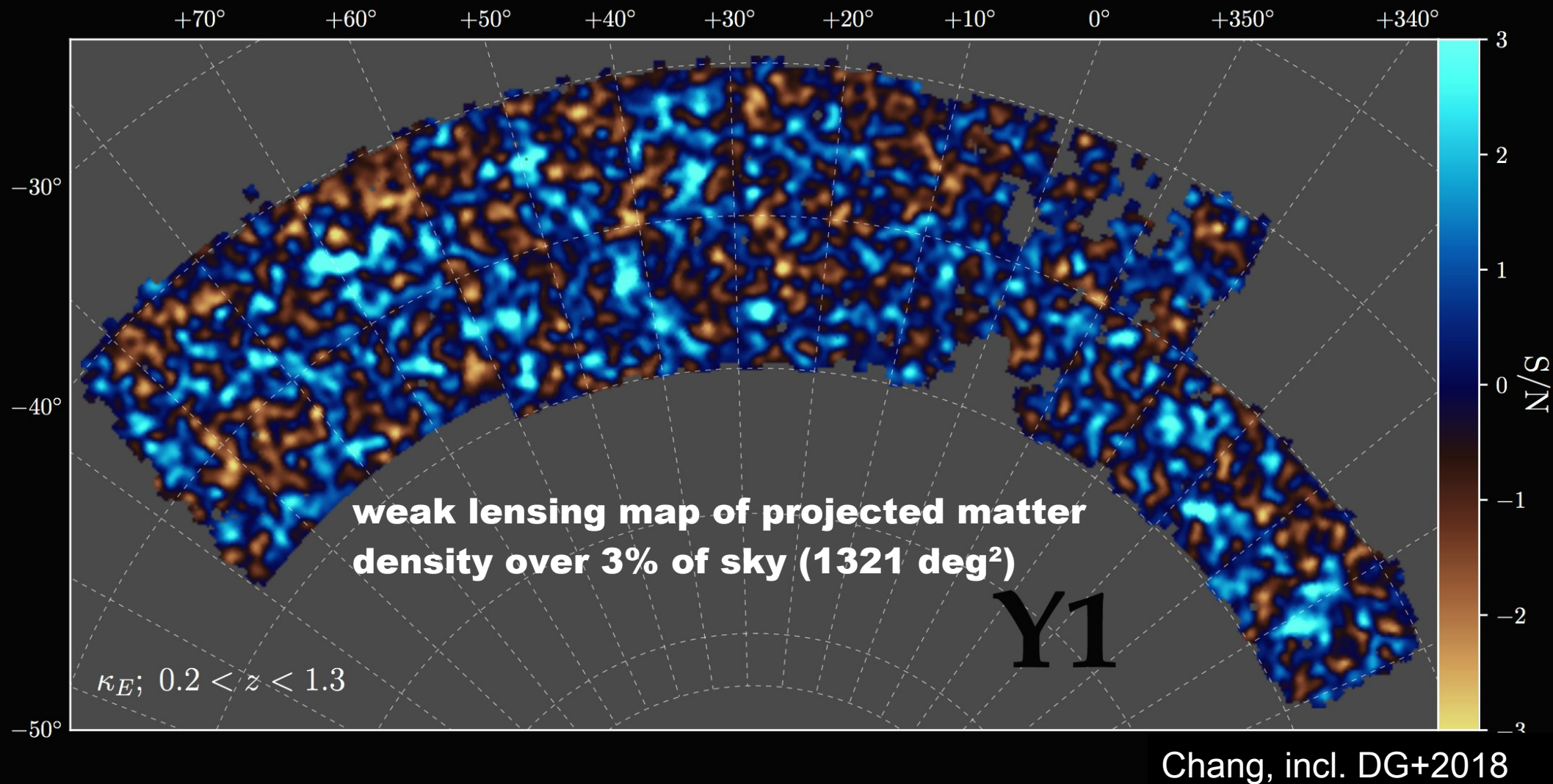
Is present-day structure low?



Cosmic Microwave Background Planck 2018

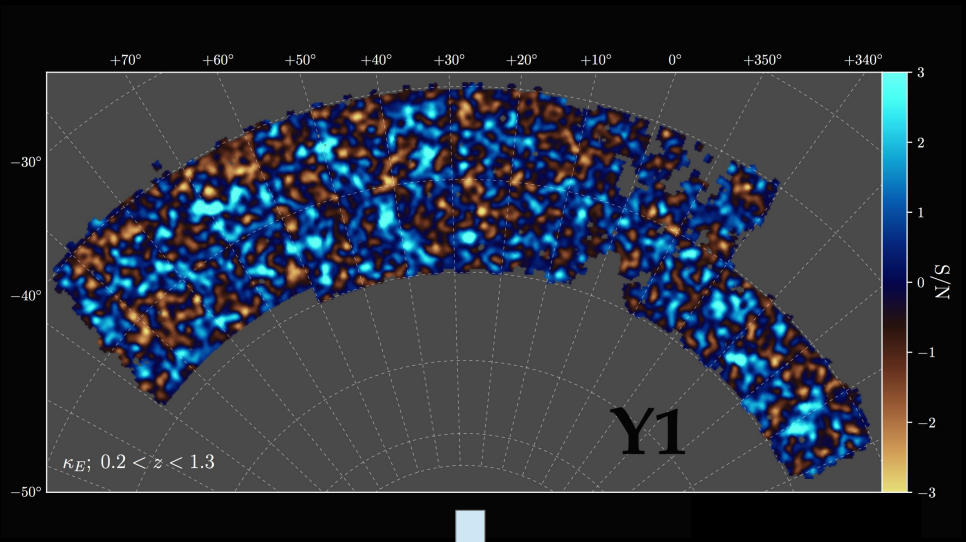
- recent studies have claimed 2-3σ offset from Planck CMB
- interpretations differ – statistical fluke, systematics, crack in ΛCDM?

DES Y1



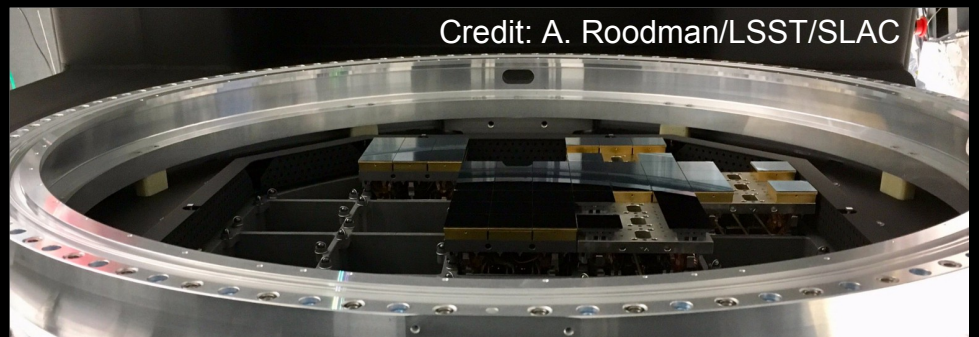
Chang, incl. DG+2018

DES Y1 … and beyond



Release	Year	Statistical power
DES Y1	2017	35M galaxies, i~22.5 1,321 sq. deg, 6/sq. arcmin <z>~0.6
DES Y3	2019	93M galaxies, i~22.5 4,100 sq. deg, 6/sq. arcmin <z>~0.6
DES Y6	2021	200M galaxies, i~23.5 5,000 sq. deg, 11/sq. arcmin <z>~0.8
LSST Y1	~2023	1200M galaxies 18,000 sq. deg, 18/sq. arcmin <z>~1.0


Credit: LSST/AURA


Credit: A. Roodman/LSST/SLAC

With great statistical power comes great systematic responsibility

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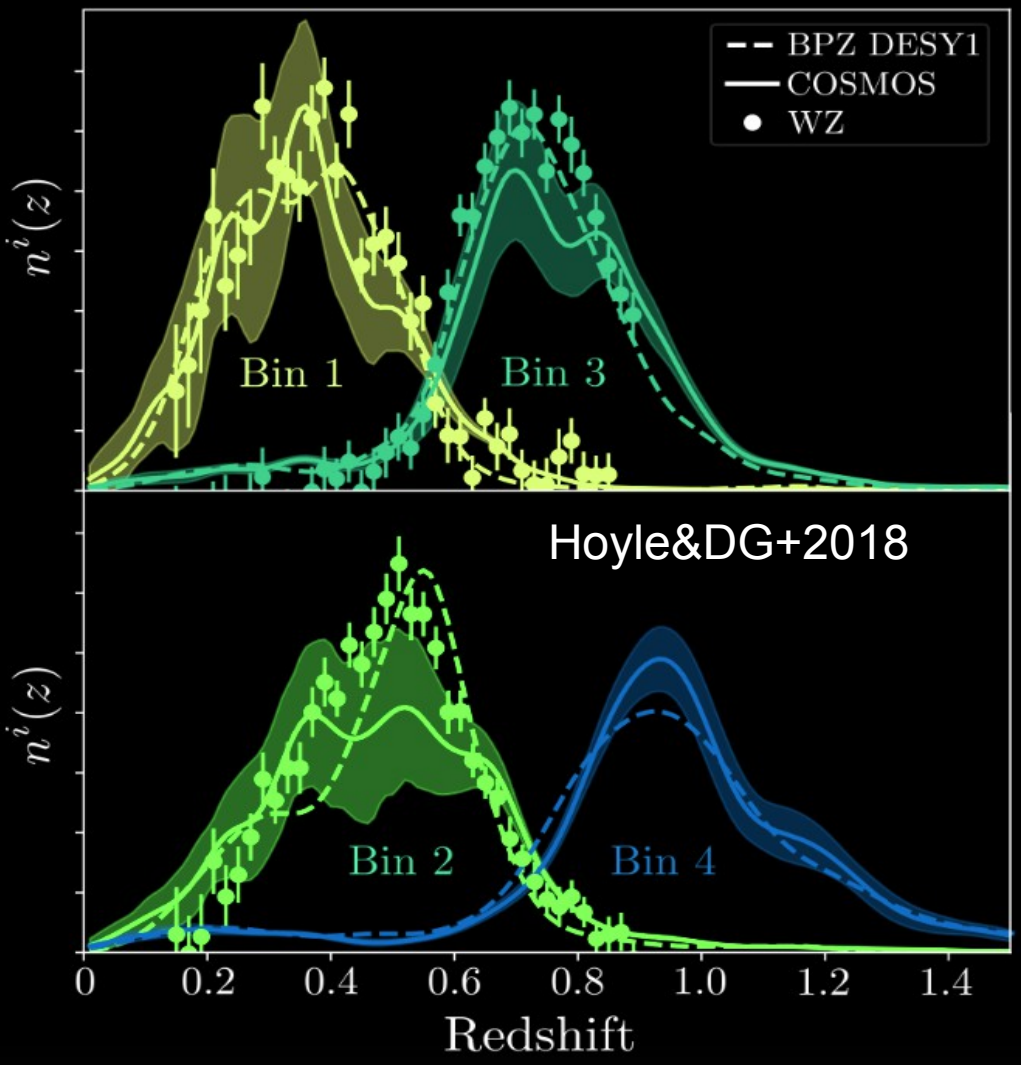
Keeping up in methodology with the gain in data volume will be a challenge

With great statistical power comes great systematic responsibility: Y1

- two independent galaxy **shape** measurement algorithms, bias <1.3% (Zuntz, Sheldon, incl. DG+2018)
- two independent calibrations of **redshifts** of four lensing source bins (Hoyle&DG+2018)
- two independent, blinded cosmological **inferences**, tested with simulations (Krause&Eifler,incl. DG+2018; MacCrann&DeRose, incl. DG+2018)

COSMOS + clustering agree,
~0.015 uncertainty on <redshift>



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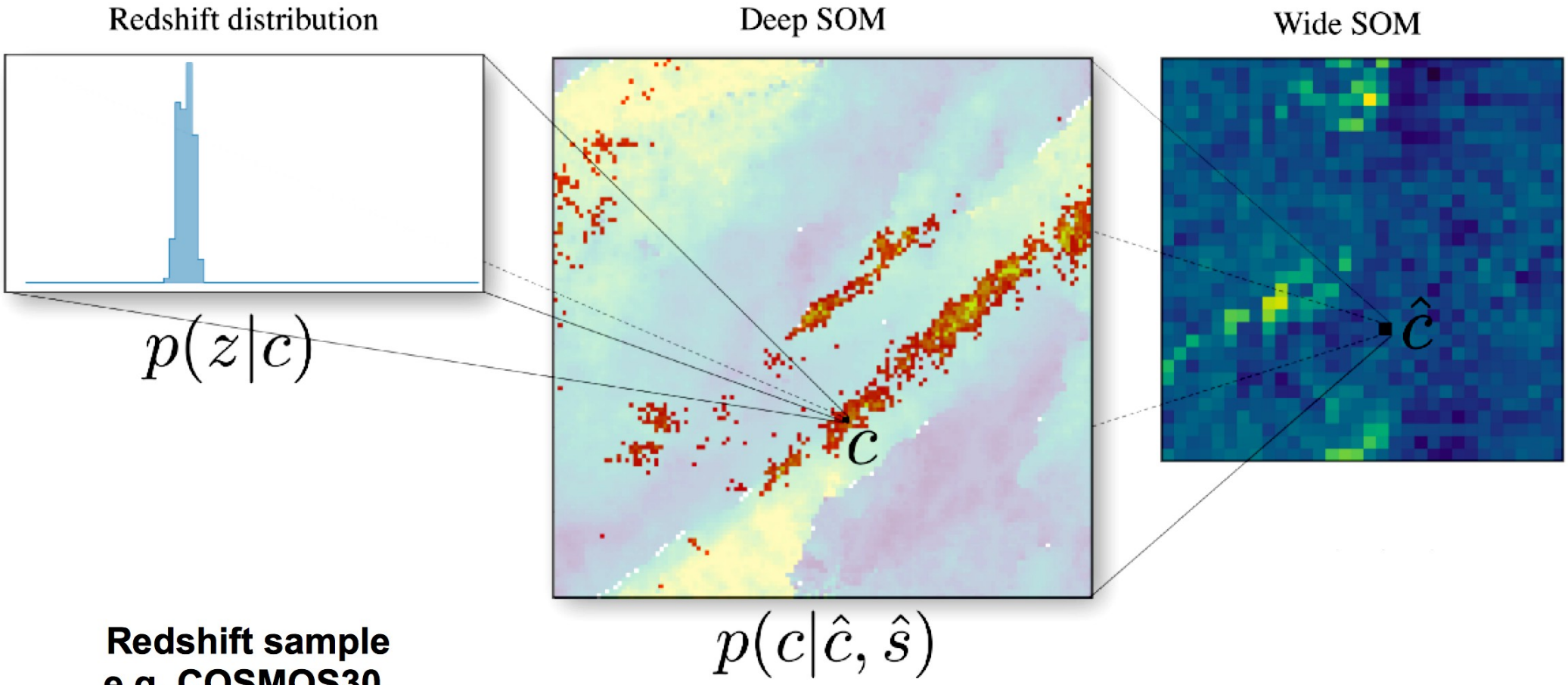

We know a way forward for redshift calibration using multi-band surveys + spectra
Buchs, Davis, DG+ 1901.05005

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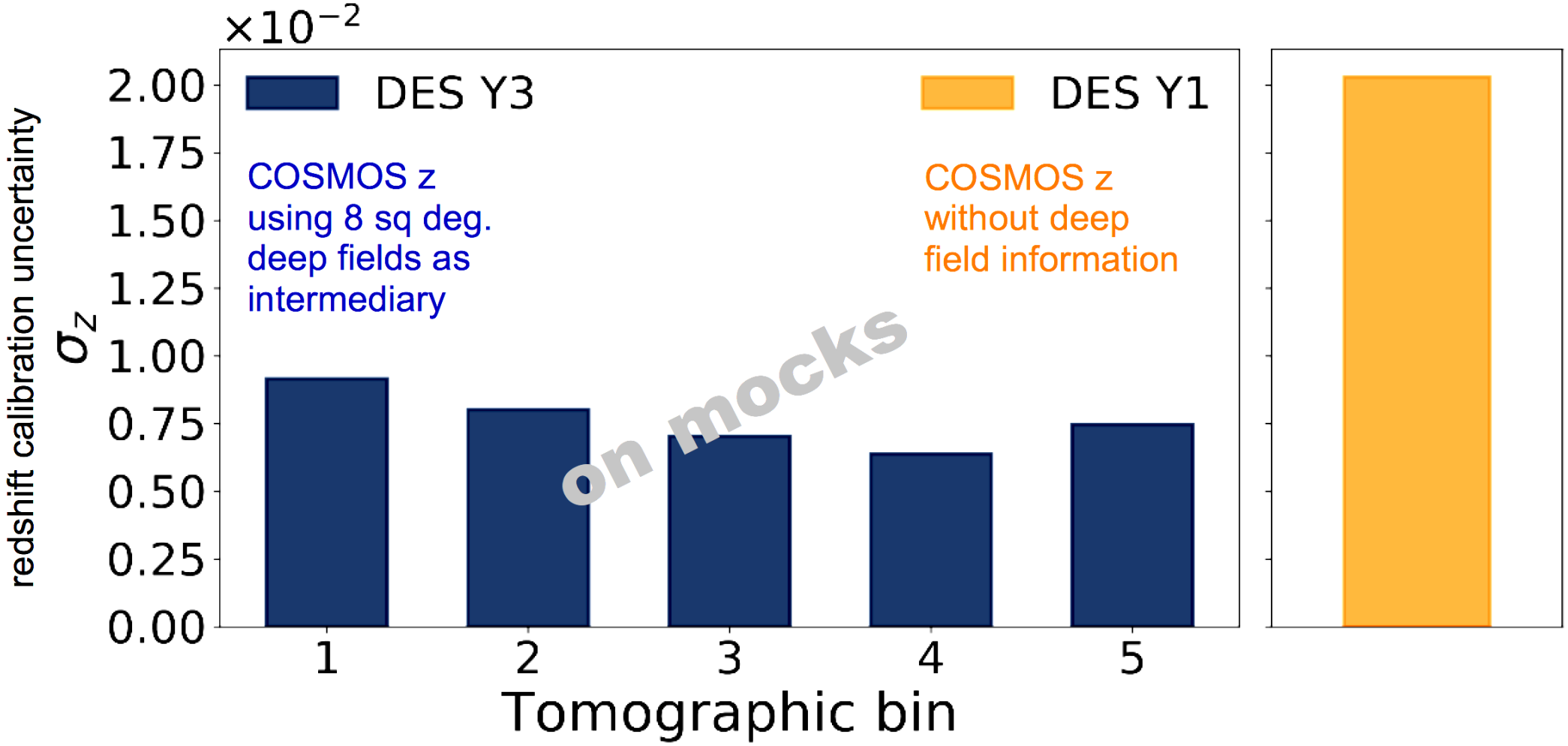

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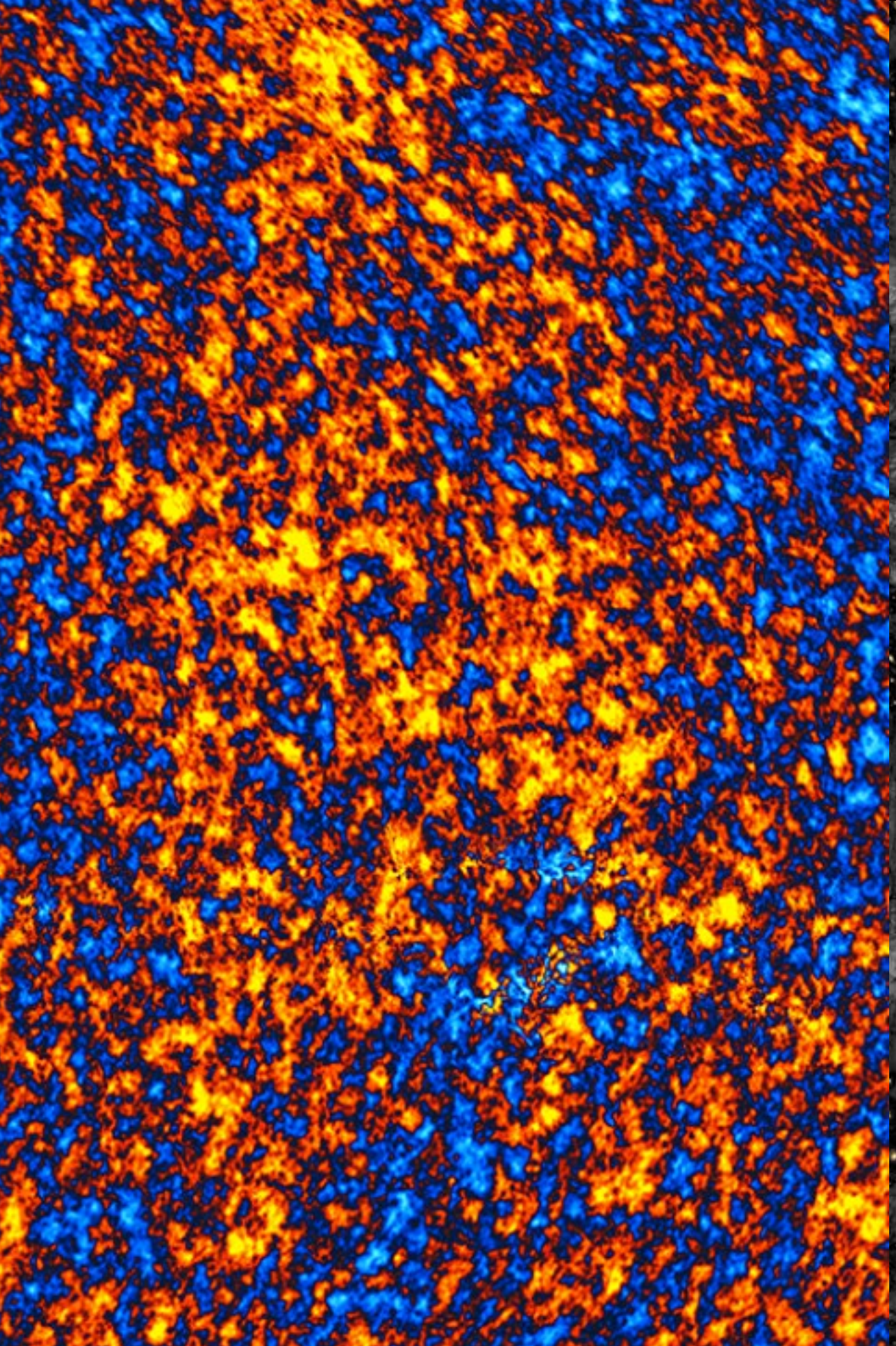
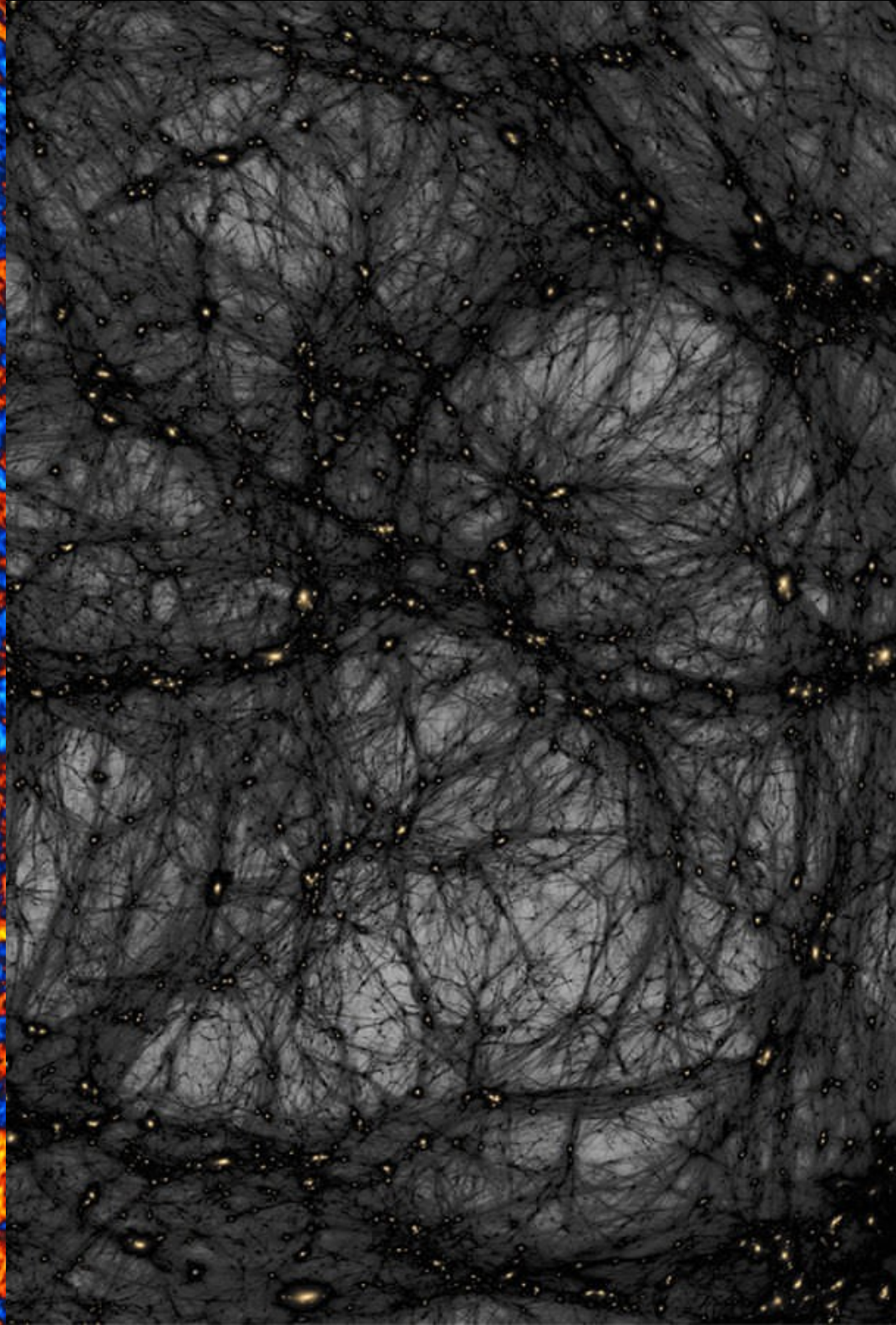
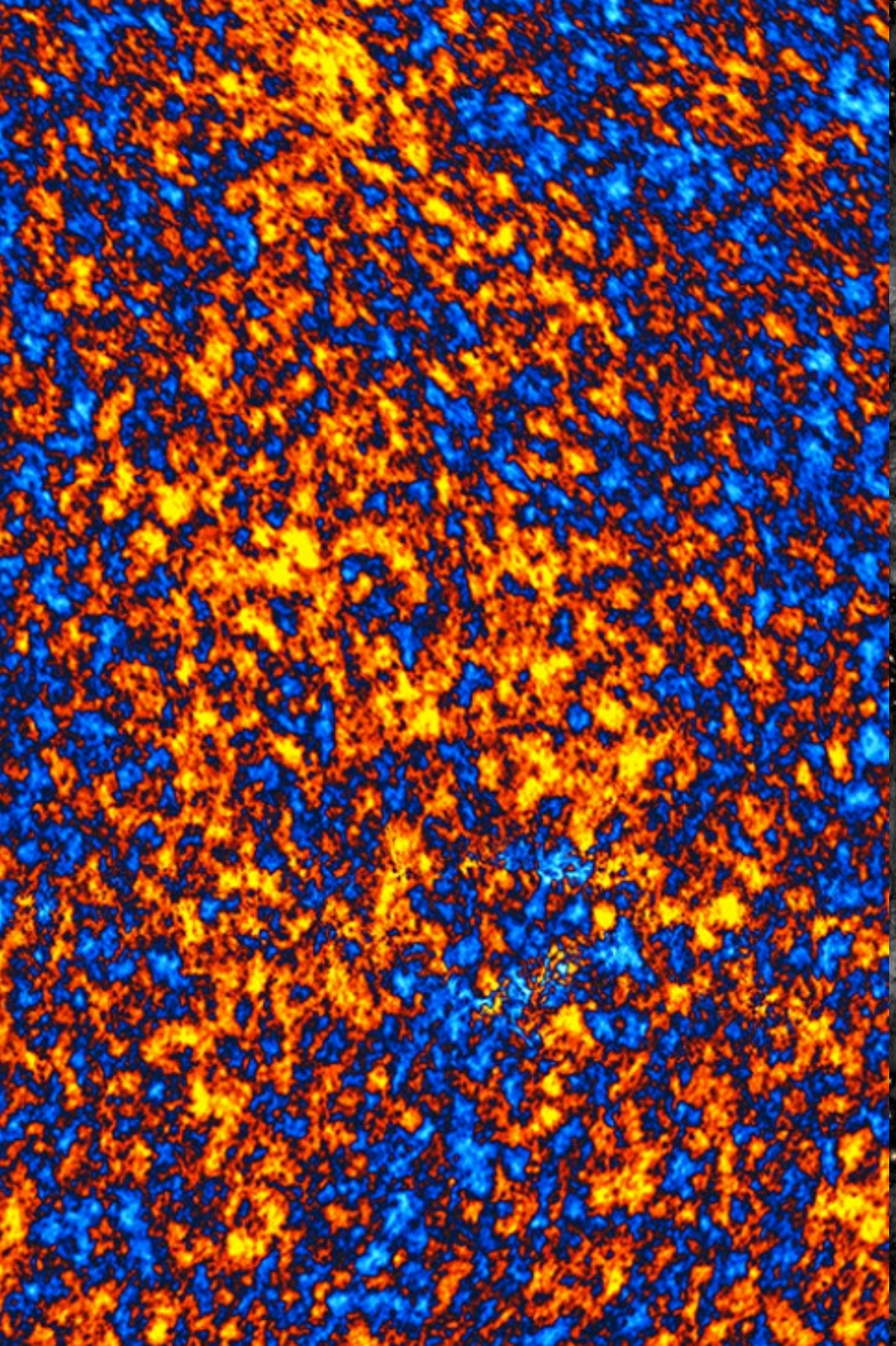
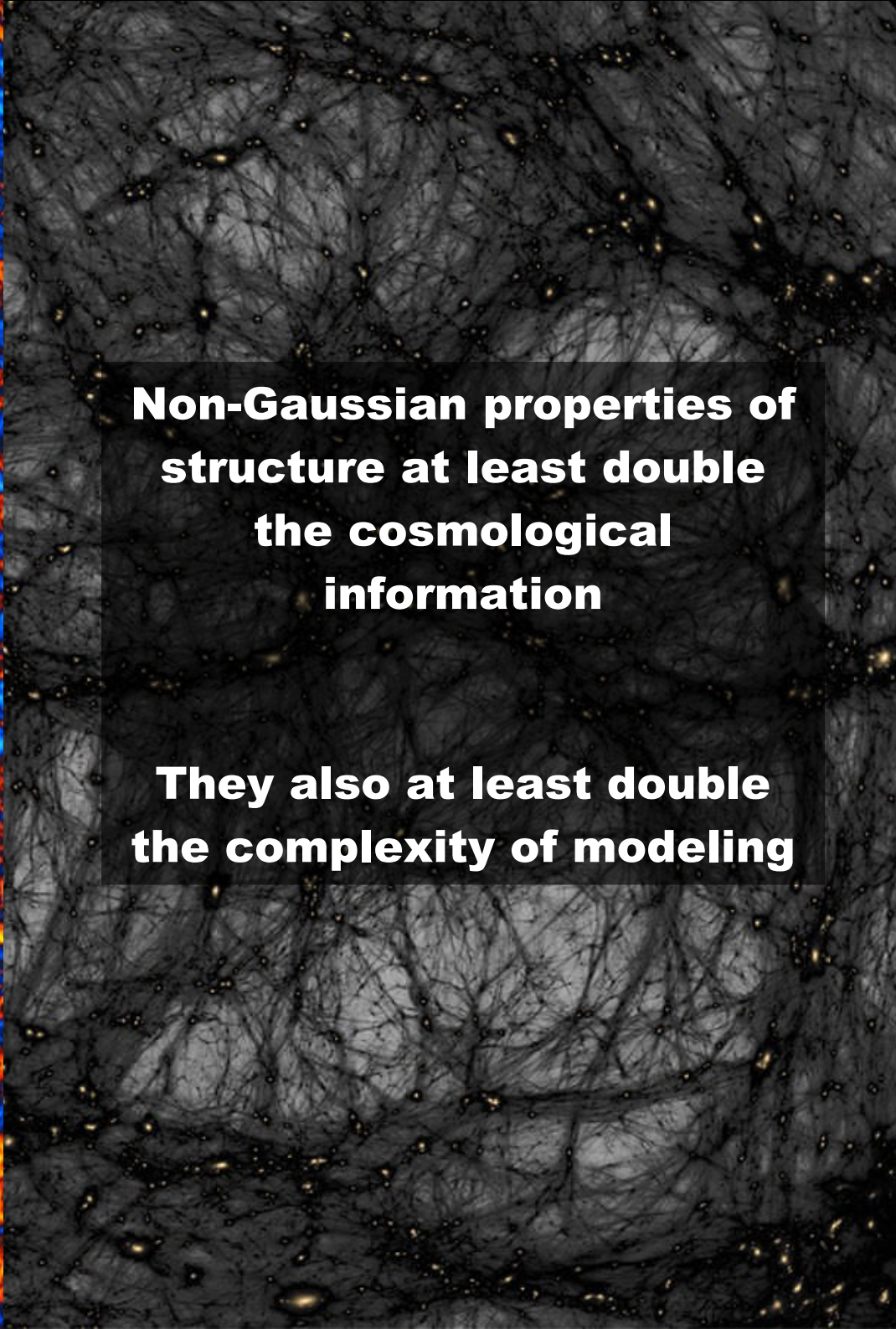



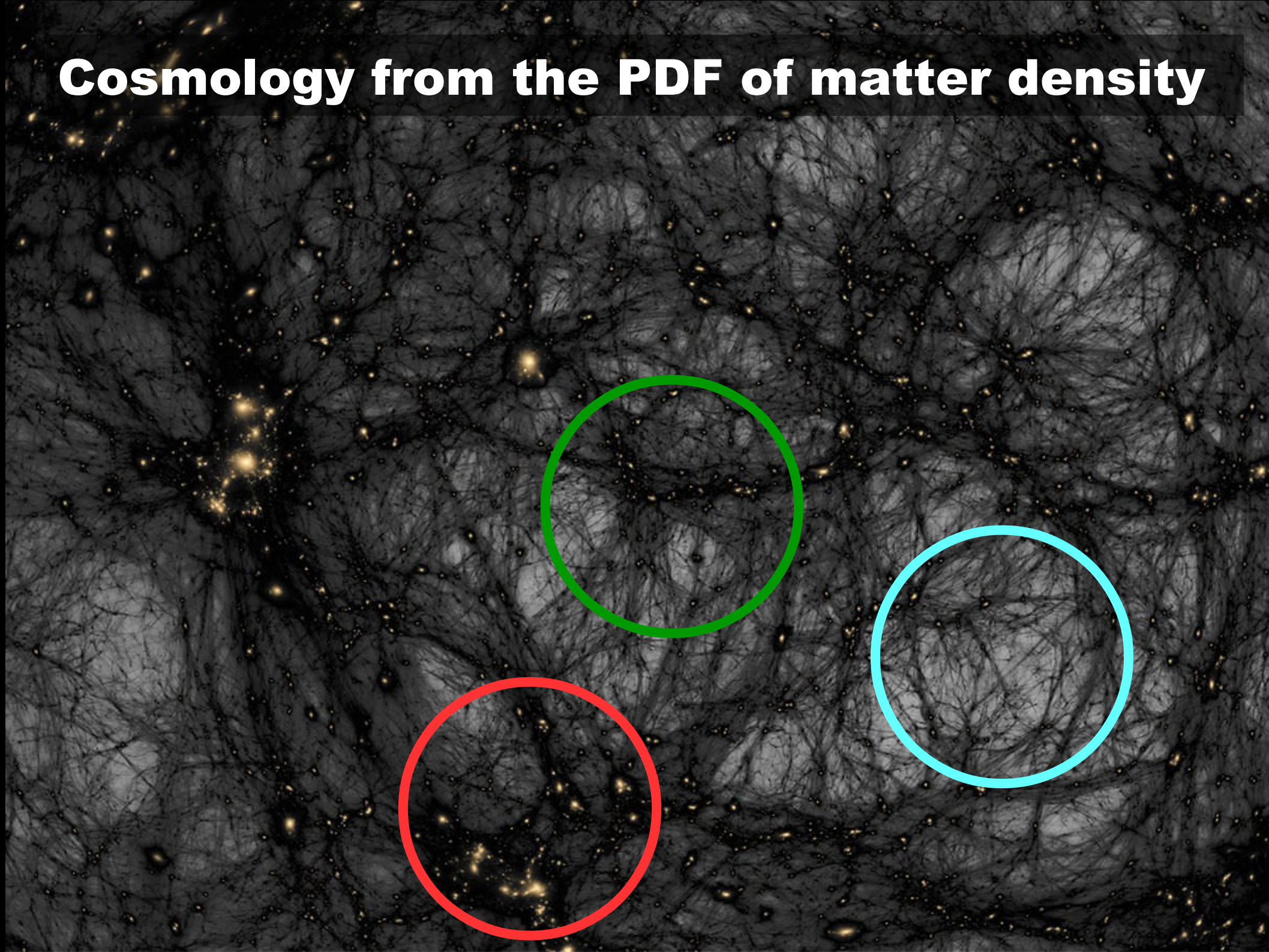




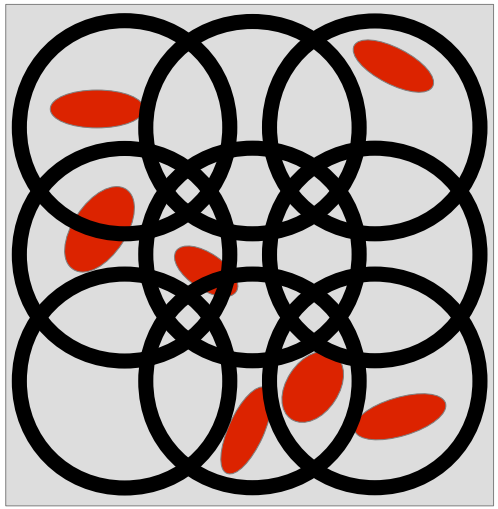
Non-Gaussian properties of structure at least double the cosmological information

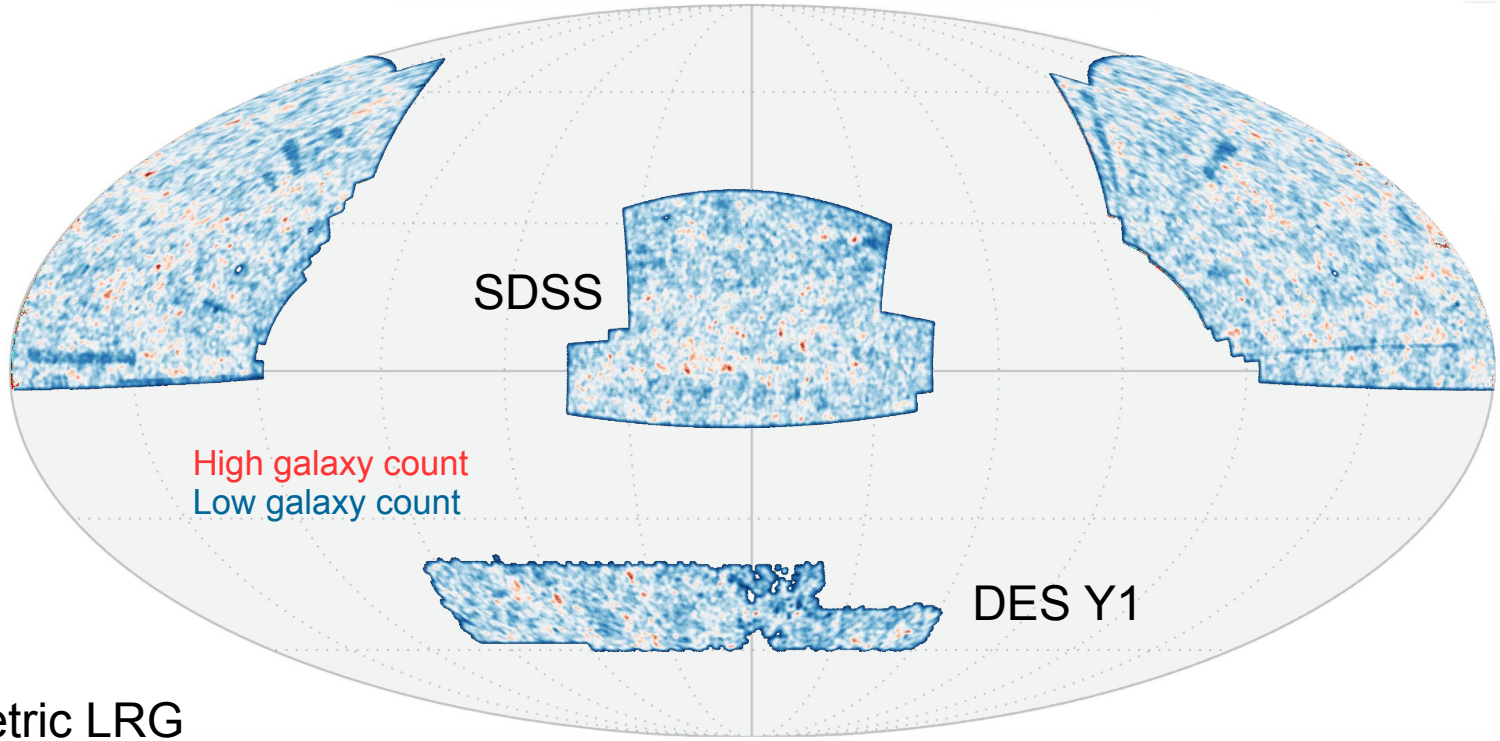
They also at least double the complexity of modeling

Cosmology from the PDF of matter density



Cosmology from matter/galaxy PDF
Step 1: Count galaxies in circles

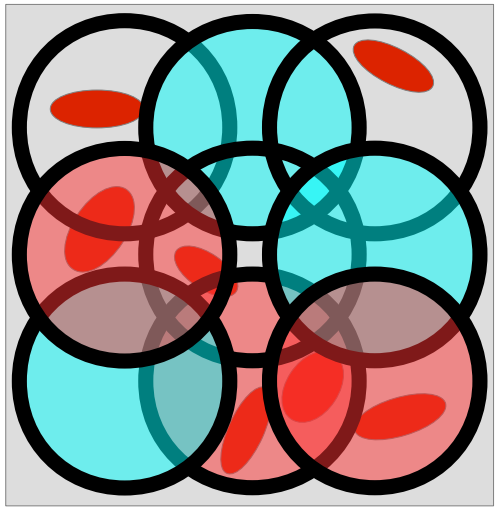


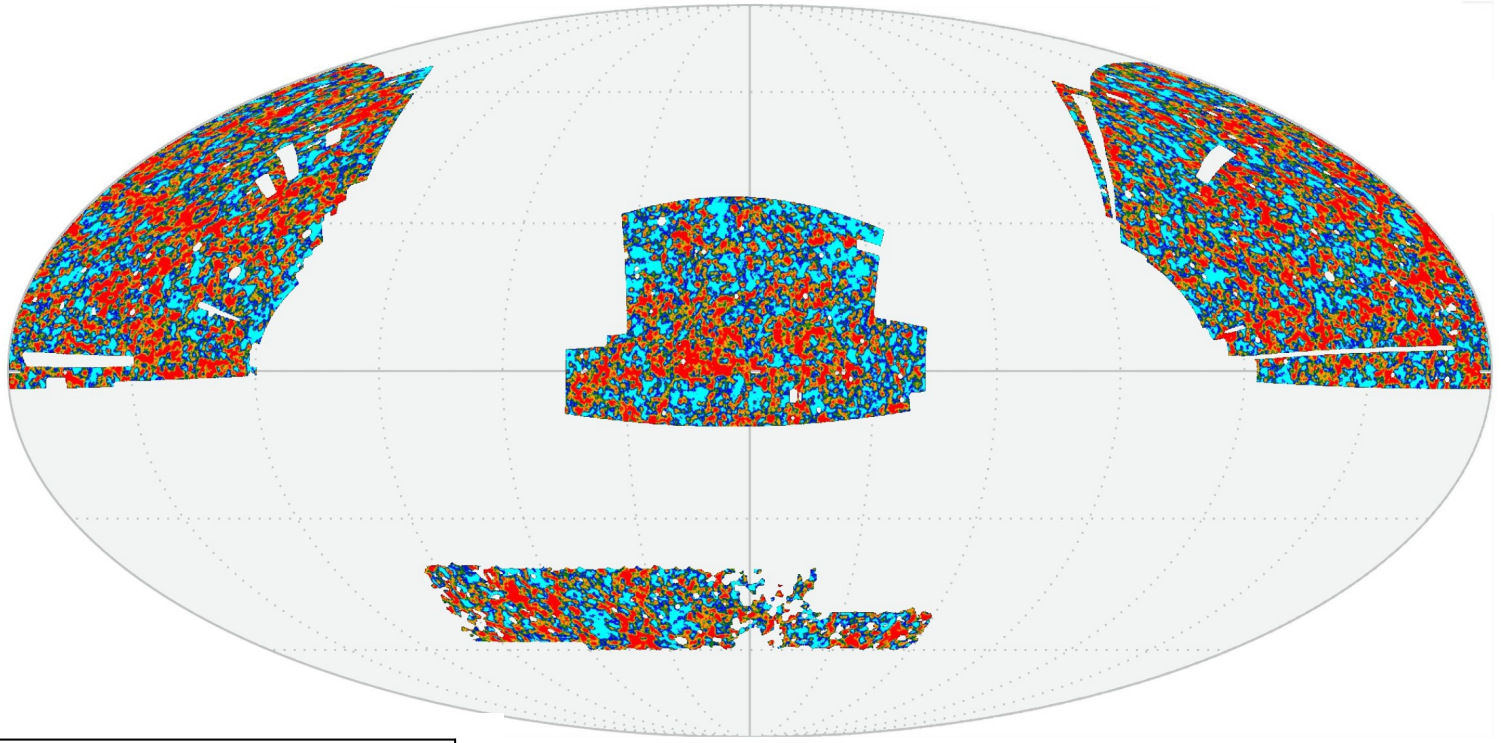


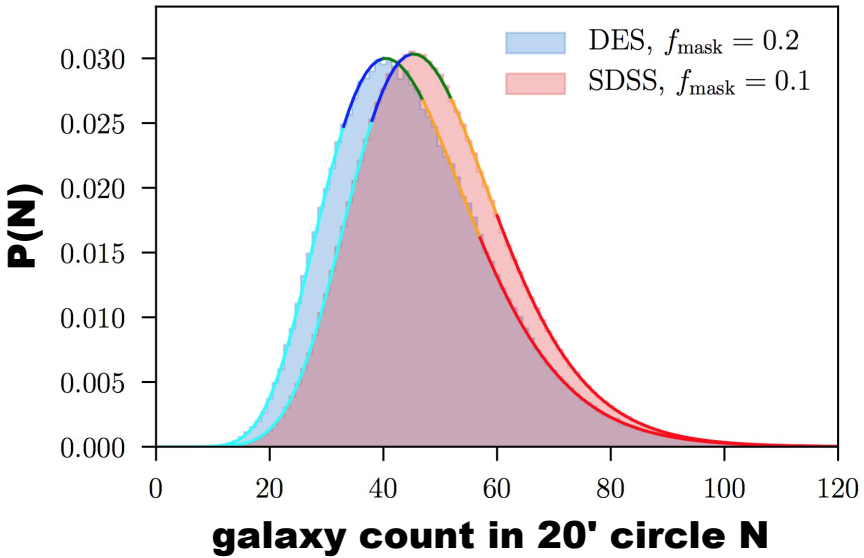
= redMaGiC photometric LRG
0.2<z<0.45, L>0.5L*

DG+ 2018

Cosmology from matter/galaxy PDF
Step 2: Divide into count quantiles



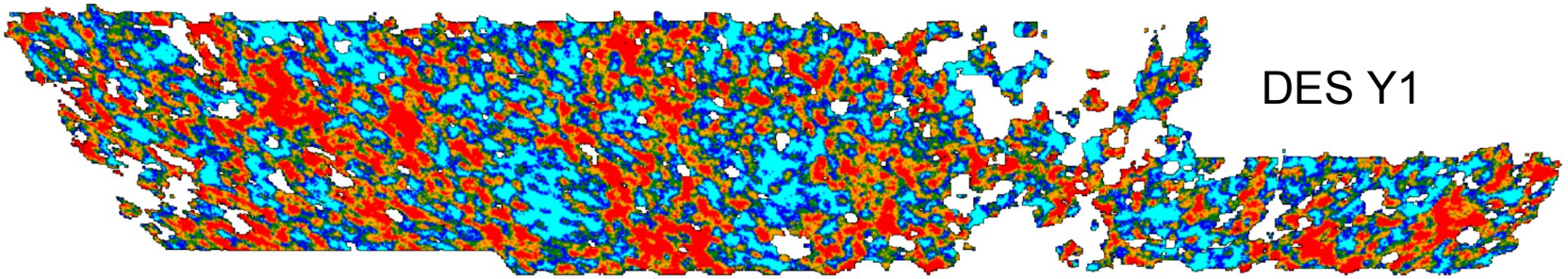


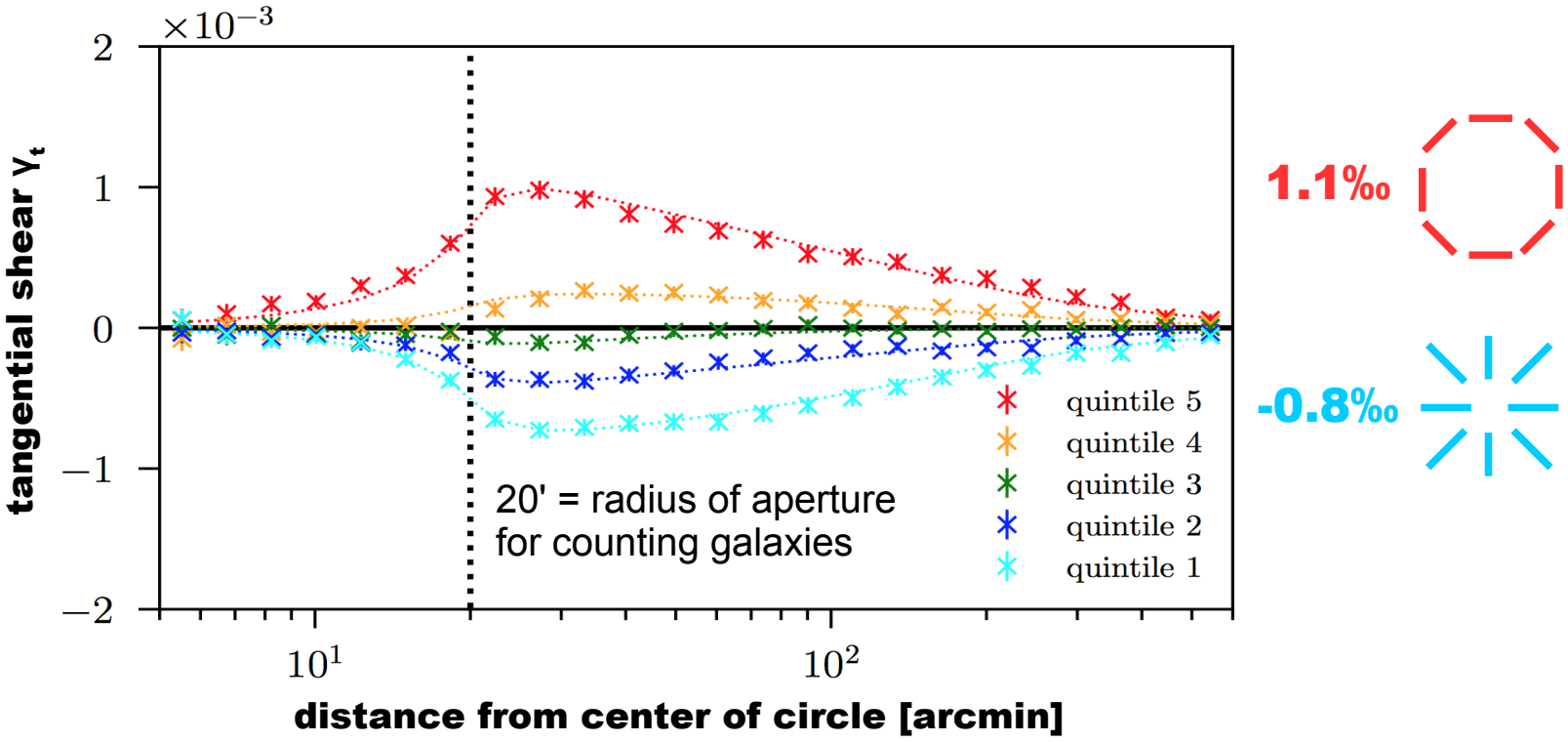


DG+ 2018

Cosmology from matter/galaxy PDF

Step 3: Measure matter density with lensing



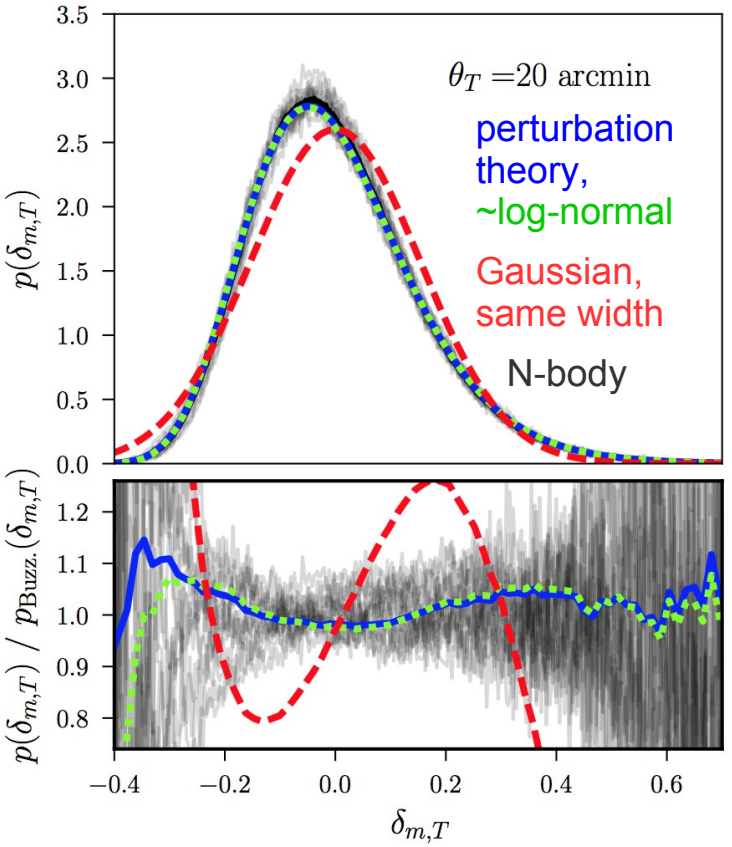


Cosmology from matter/galaxy PDF

Step 4: Model

Ingredients:

- Matter density PDF $p(\delta_m)$ from simulations or perturbation theory
- Galaxy bias $P(N|\delta_m)$
- Matter density → lensing shear $\gamma_t(\delta_m)$



$$\langle \gamma_t \rangle(N) = \int p(\delta_m|N)\, \langle \gamma_t \rangle(\delta_m)\, \mathrm{d}\delta_m$$

perturbation theory model:
Friedrich, DG+ 2018

Cosmology from matter/galaxy PDF: testing skewness

- Lensing + counts in cells add a test of gravity:
  - Skewness of matter density:

$$S_3 \equiv \frac{\langle \delta_{\rm m}^3 \rangle}{\langle \delta_{\rm m}^2 \rangle^2}$$

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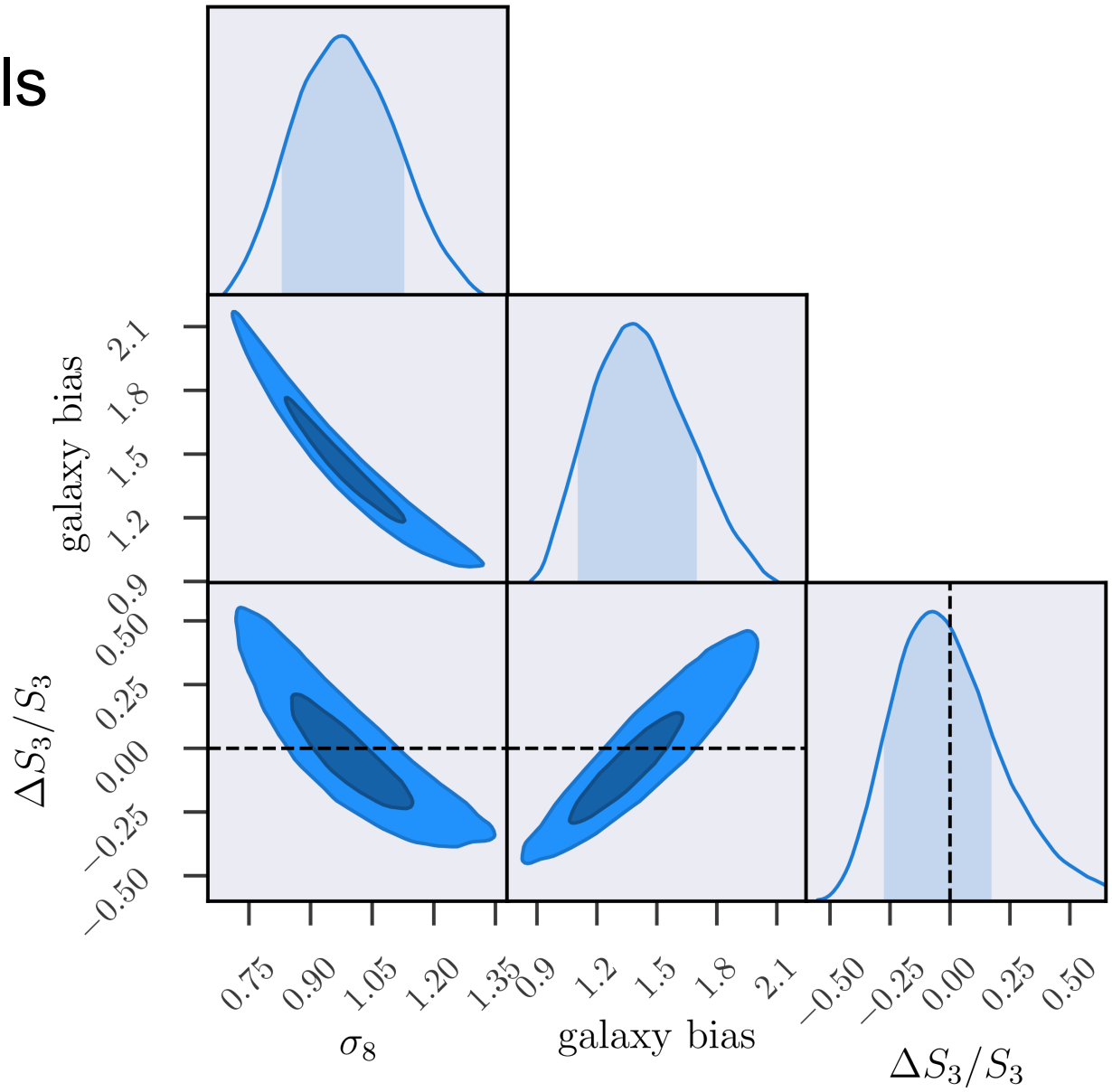

Cosmology from matter/galaxy PDF: skewness informs cosmology

- Lensing + counts in cells add a test of gravity:
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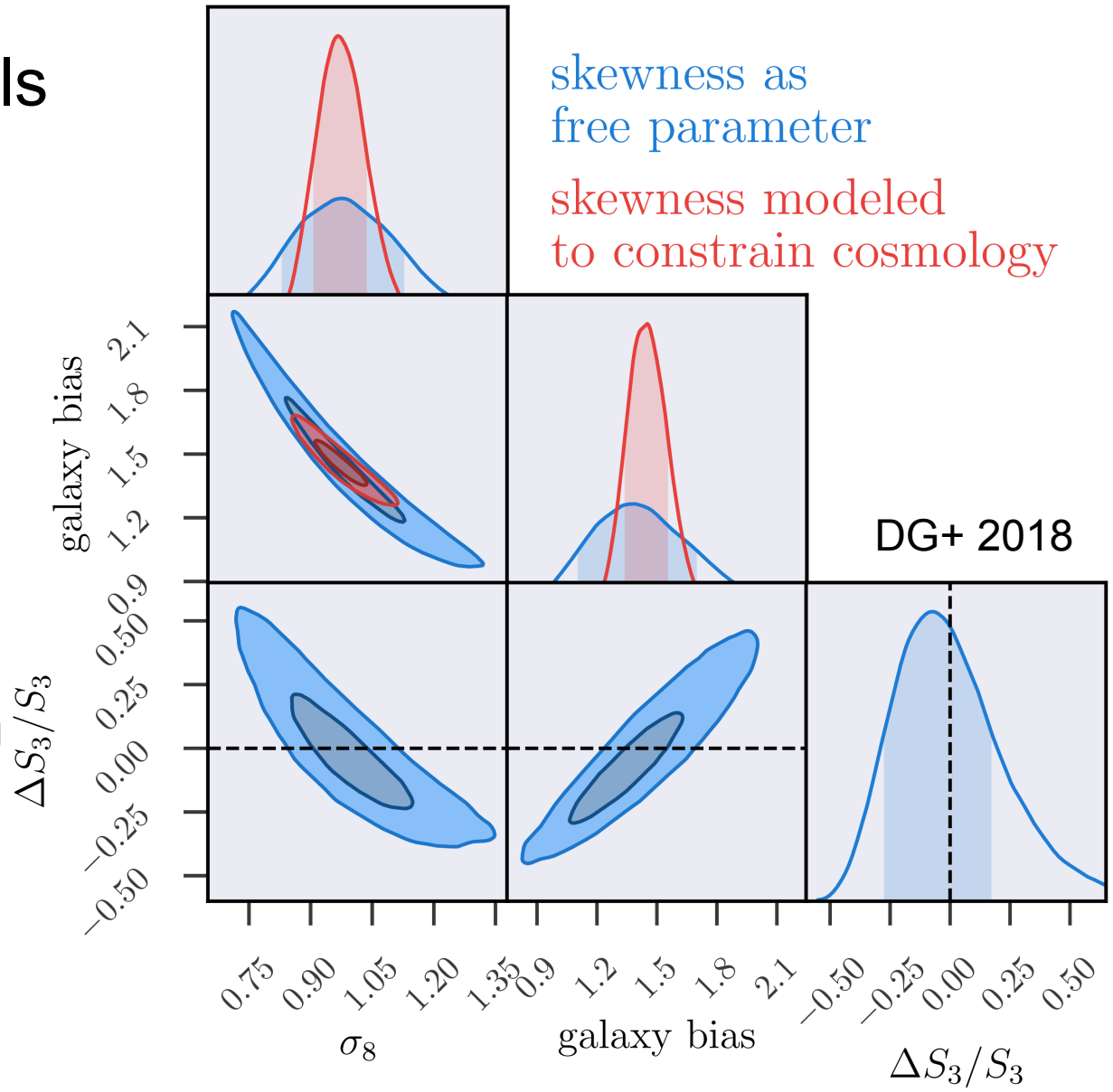
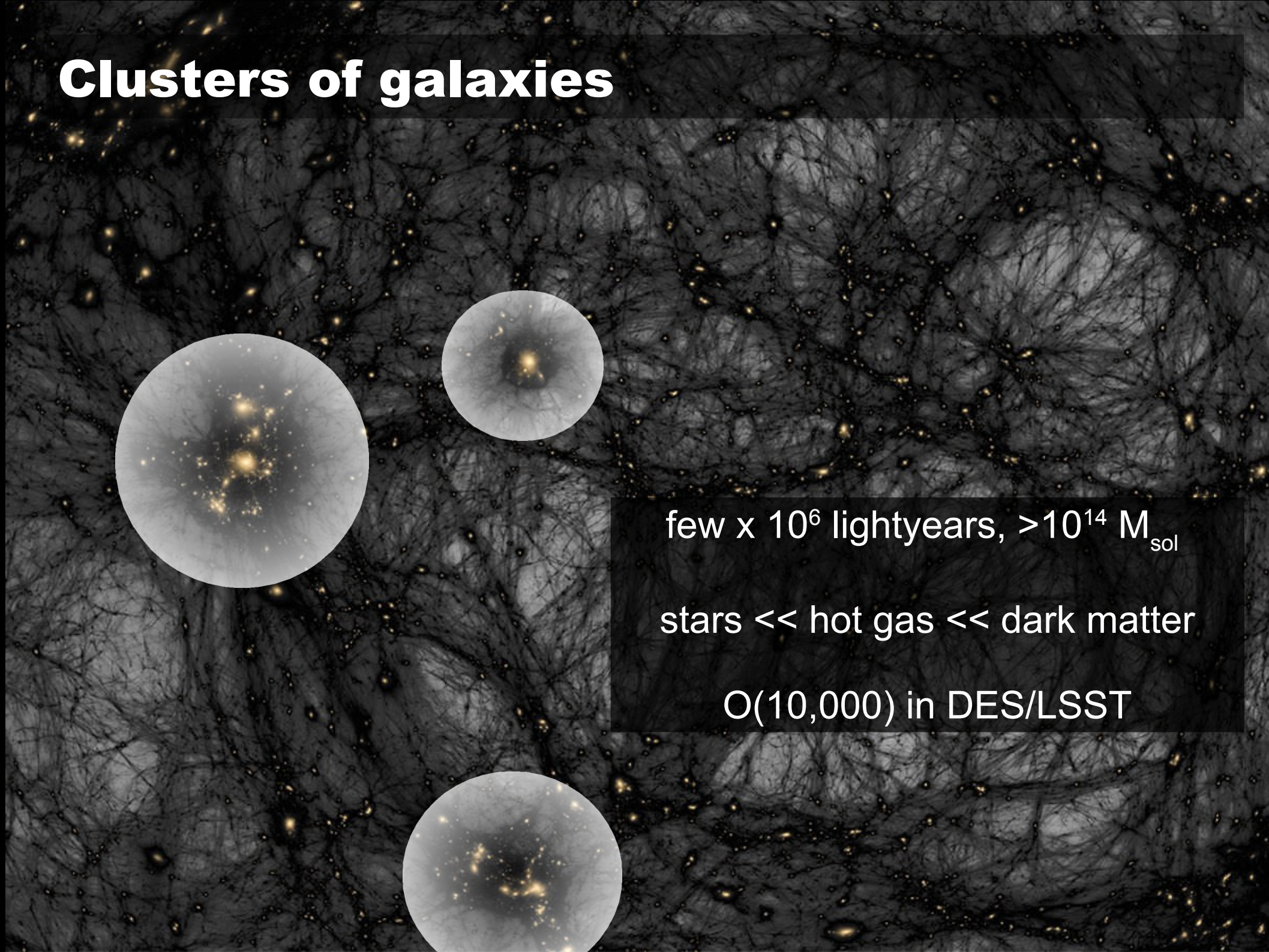
$$S_3 \equiv \frac{\langle \delta_{\rm m}^3 \rangle}{\langle \delta_{\rm m}^2 \rangle^2}$$

- Non-Gaussianity adds significant information on cosmology and bias



Clusters of galaxies

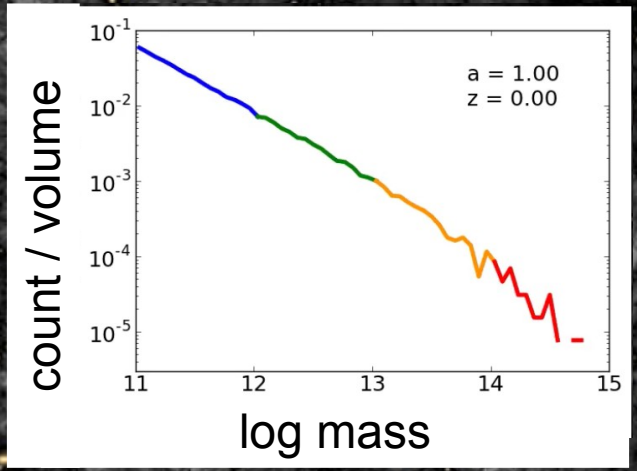


few x 10^6 lightyears, >10^{14} M_{sol}

stars << hot gas << dark matter

O(10,000) in DES/LSST

Clusters of galaxies in optical surveys



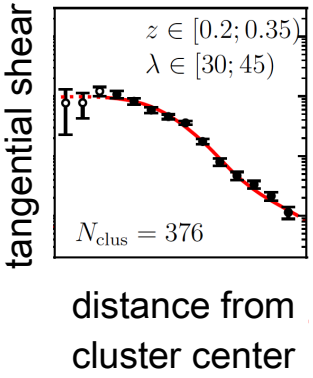
prediction: n(mass)

richness =
count of bright
elliptical galaxies

p(richness|mass) = ?

Cosmology with clusters of galaxies: Mass calibration with lensing

- Large area lensing surveys
  are the best way of calibrating
  <mass|observable> of clusters



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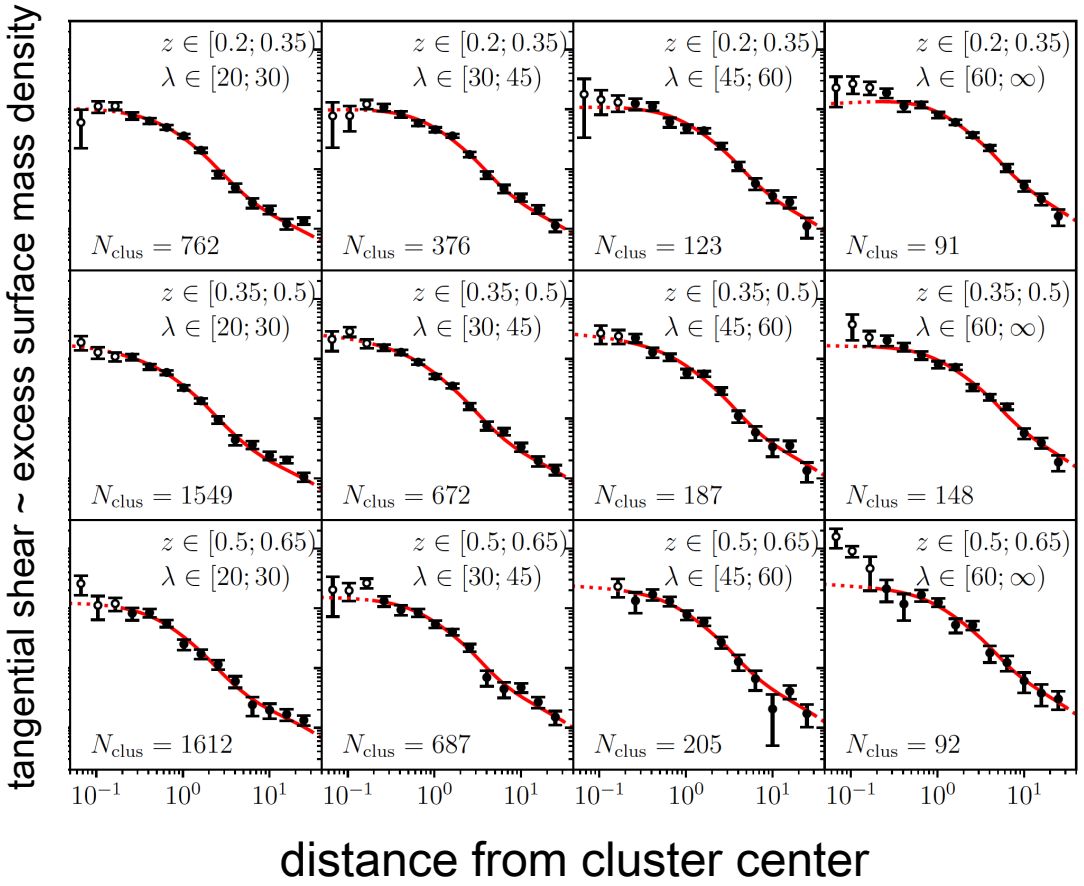
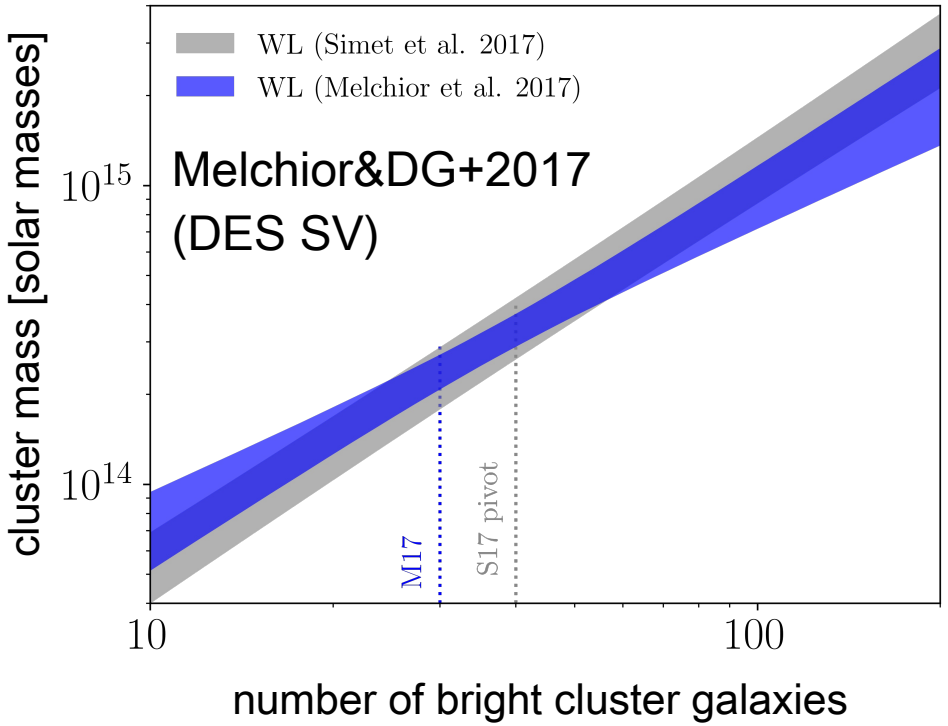
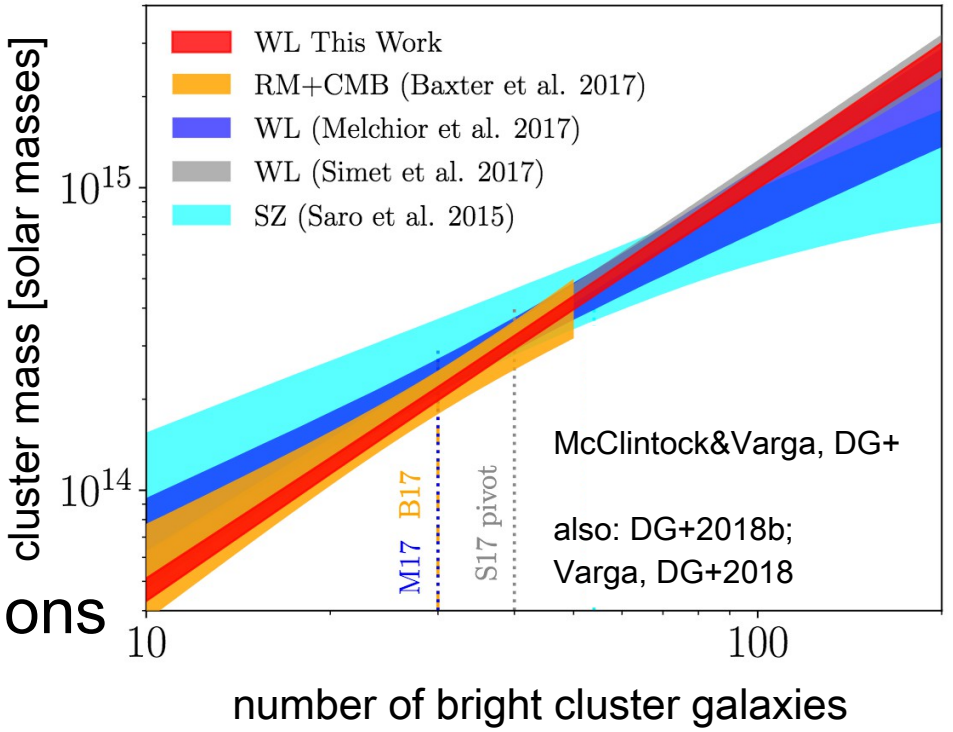




Cosmology with clusters of galaxies: Mass calibration with lensing

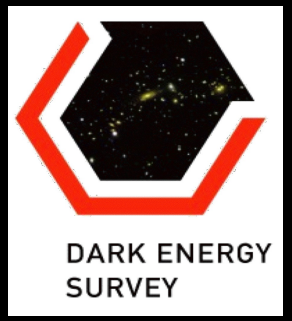
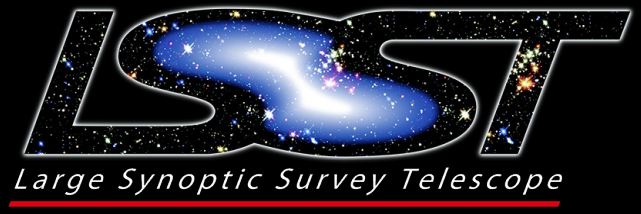
- Large area lensing surveys are the best way of calibrating <mass|observable> of clusters
- Uncertainties dominated by modeling (projections!) and photo-z
- Way forward: external data, simulations constraining power ~ 3x2pt!



Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncertainty
Shear measurement	4%	1.7%
Photometric redshifts	3%	2.6%
Modeling systematics	2%	0.73%
Cluster triaxiality	2%	2.0%
Line-of-sight projections	2%	2.0%
Membership dilution + miscentering	$\leqslant$ 1%	0.78%
Total Systematics	6.1%	4.3%
Total Statistical	9.4%	2.4%
Total	11.2%	5.0%

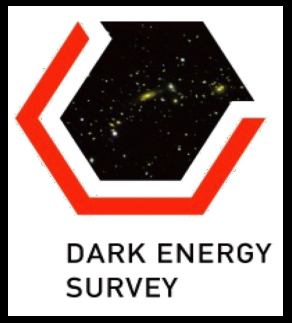
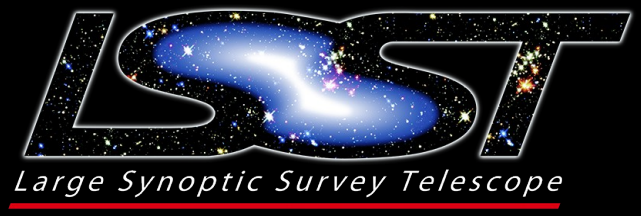
photo-z

Modeling / projections

From  to 

Measurements

- galaxy shapes
- redshift distributions
- faint & blended frontier

From  to 

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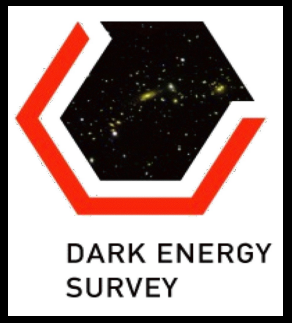
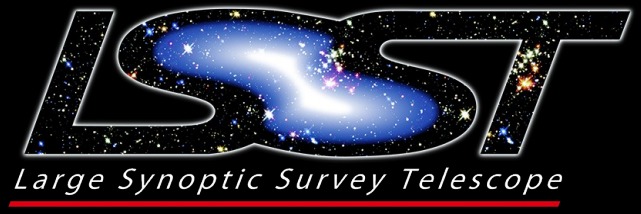
External data

- Spectroscopy / DESI
- Narrow-band surveys
- X-ray, SZ clusters
- CMB-S4

From  to 

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- beyond power spectrum
- simulation as model

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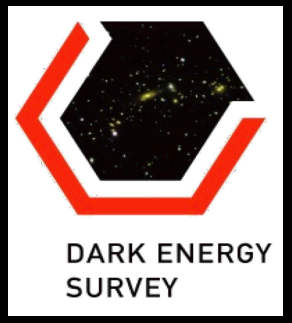
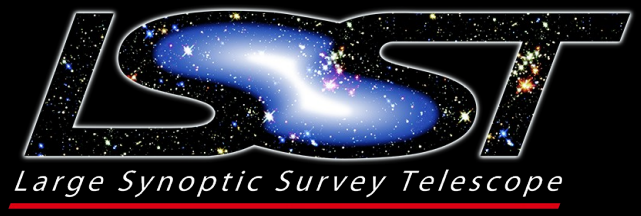
From  to 

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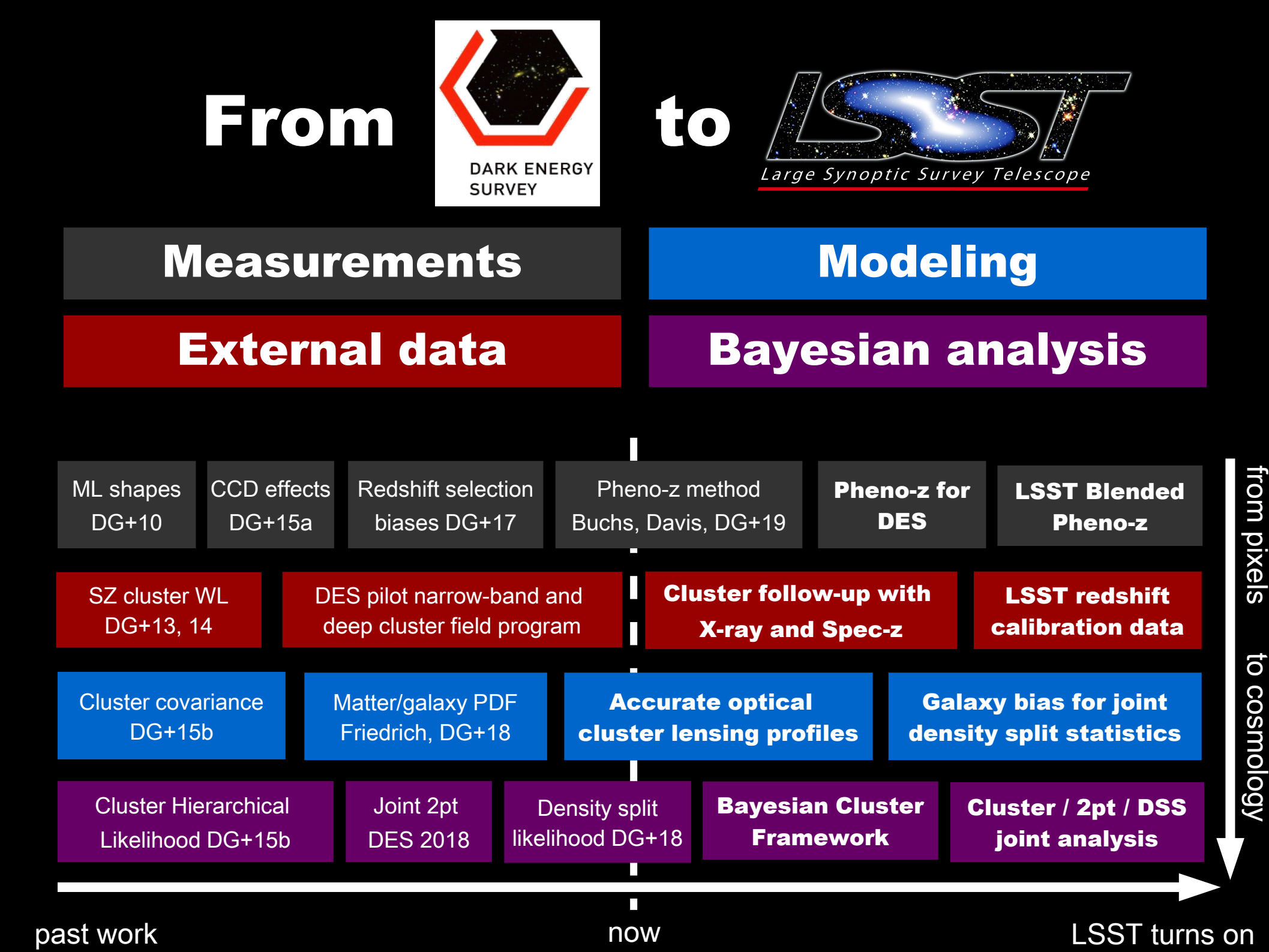
Bayesian analysis

- Covariance
- Bayesian hierarchical: clusters
- Joint probes


From
DARK ENERGY SURVEY
to
Large Synoptic Survey Telescope
Measurements
Modeling
External data
Bayesian analysis
ML shapes DG+10
CCD effects DG+15a
Redshift selection biases DG+17
Pheno-z method Buchs, Davis, DG+19
Pheno-z for DES
LSST Blended Pheno-z
SZ cluster WL DG+13, 14
DES pilot narrow-band and deep cluster field program
Cluster follow-up with X-ray and Spec-z
LSST redshift calibration data
Cluster covariance DG+15b
Matter/galaxy PDF Friedrich, DG+18
Accurate optical cluster lensing profiles
Galaxy bias for joint density split statistics
Cluster Hierarchical Likelihood DG+15b
Joint 2pt DES 2018
Density split likelihood DG+18
Bayesian Cluster Framework
Cluster / 2pt / DSS joint analysis
from pixels to cosmology
past work
now
LSST turns on

From DARK ENERGY SURVEY to LSST Large Synoptic Survey Telescope

Measurements

Modeling

External data

Bayesian analysis

DES and LSST lensing as an **accurate probe** of dark energy and dark matter

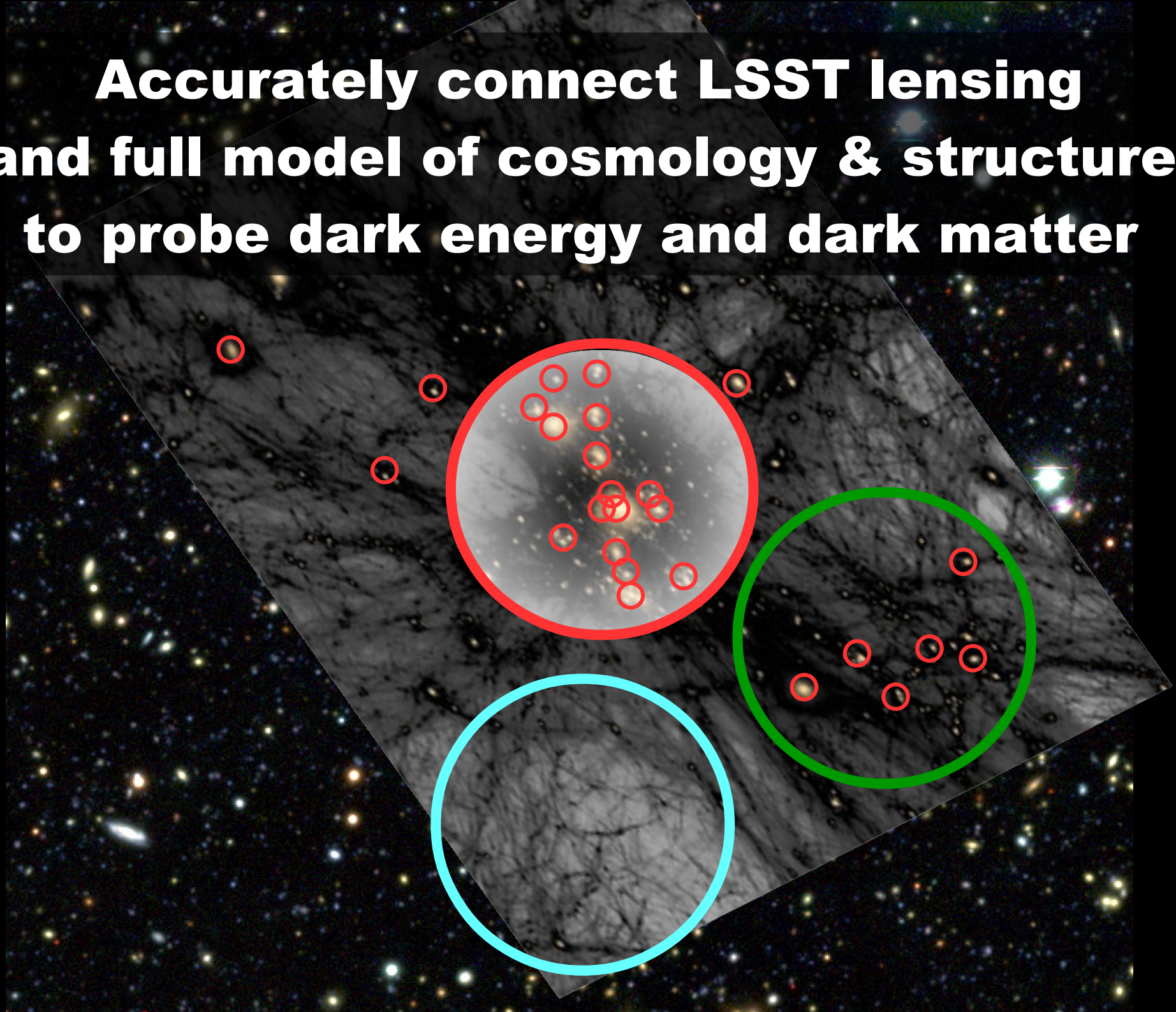
Stress-testing **dark energy** and **dark matter** with **non-Gaussian** structure

Connecting DES and LSST to external **data** from DESI, CMB-S4, and dedicated programs

LSST Dark Energy Science @ SLAC PAC

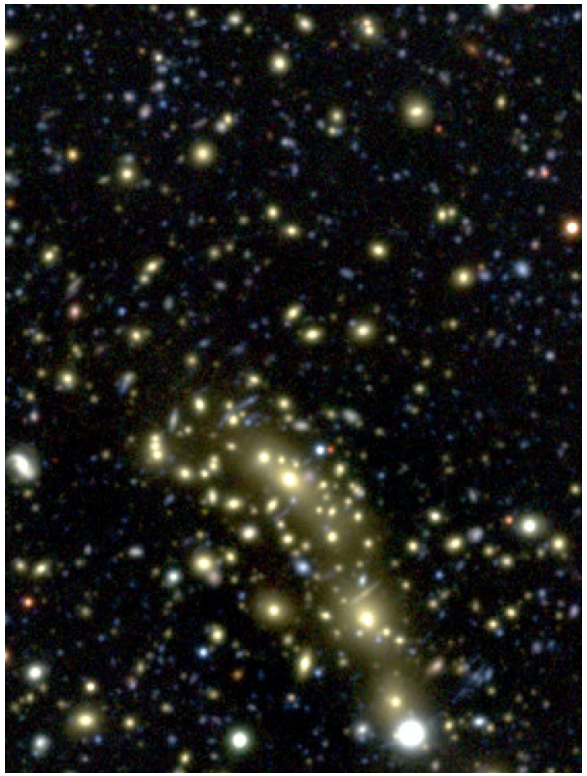

DES observations at ~LSST Y5 depth

Accurately connect LSST lensing and full model of cosmology & structure to probe dark energy and dark matter

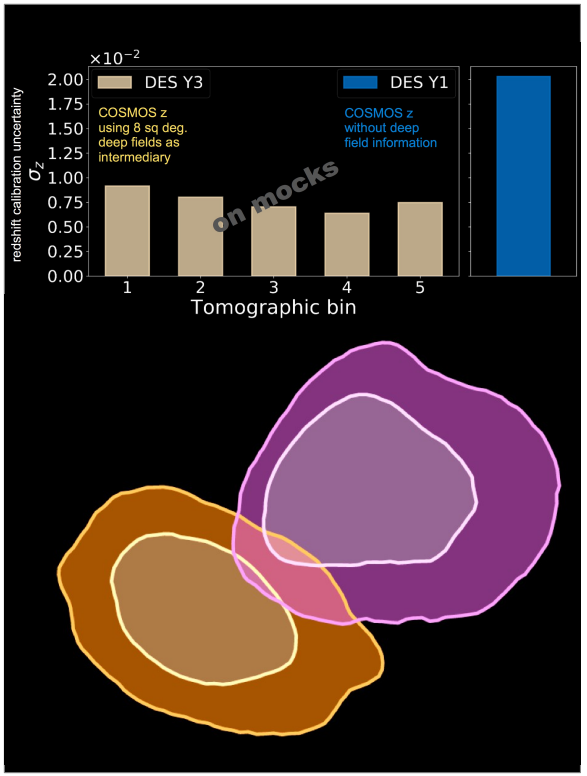


Unprecedented data from DES & LSST

Large Synoptic Survey Telescope



Precise & accurate lensing analyses



Testing structure beyond the power spectrum